TOWARDS ELECTRICAL ISOLATED SYSTEMS BASED ON 100% RENEWABLES

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I. Resumo

O desenvolvimento socioeconómico e as mudanças climáticas constituem seguramente os dois maiores desafios das comunidades dispersas pelo Planeta em centenas de milhares de ilhas remotas. Para além dos custos adicionais no aprovisionamento de combustíveis, as ilhas distantes dos Continentes enfrentam crescentes restrições devidas aos constrangimentos da mudança climática que põem em causa a sua sobrevivência e da inacessibilidade das novas tecnologias que lhes permitam tirar partido dos recursos naturais locais de forma economicamente acessível. Mas se as energias renováveis representam definitivamente a solução, para além da inovação tecnológica, levantam-se problemas de planeamento e de identificação das verdadeiras necessidades tendo em conta modernos conceitos de suficiência energética e adequadas estratégias de eficiência desde a fonte de energia [1], nas redes e no uso daquela directamente ou convertida, nomeadamente, em electricidade.

Num tal cenário, faz-se nesta tese uma abordagem metodológica de um caso que gradualmente pudesse levar à satisfação de todas as necessidades energéticas por electricidade 100% renovável.

Após a pré-selecção das tecnologias adequadas aos recursos energéticos naturais disponíveis e a consideração das características locais, todas as potenciais tecnologias são sujeitas a um processo de decisão por análise multicritério. Os aspectos tecnológicos, económicos, ambientais e sociais são analisados para identificar quais as fontes de energia renovável e as tecnologias que são as mais adequadas ao caso. Dado que vários critérios são considerados, os responsáveis por tomadas de decisão podem escolher nomeadamente as alternativas de geração, 'onshore' e 'offshore'.

Com recurso a uma análise por séries temporais faz-se a comparação de custos entre os diversos cenários considerados para a electricidade incluindo o papel e o custo do armazenamento combinado com diferentes alternativas de geração. Para tal são utilizadas séries temporais horárias para um período de ciclo anual. São avaliadas, tento ainda em consideração, estratégias que reduzem o custo global do sistema, bem como considerações sobre a introdução de contribuição menores de combustíveis fósseis. Finalmente, procede-se a uma análise de sensibilidade.

No caso de estudo da ilha de S. Miguel, Açores, é prevista uma procura de electricidade com crescimento constante. Dois tipos de perfil de carga foram considerados: o perfil corrente e um alternativo com variações da carga do nível de ponta às do nível de 'baixa' com várias medidas de redução da carga. Para cada fonte de energia a ser explorada foi elaborada uma pré-selecção das tecnologias. Apesar da disponibilidade de algumas fontes, tendo em conta as suas localizações, a exploração de alguns recursos (vento 'offshore', marés, alguma 'hydro' e geotermia e muita da bioenergia) foi excluída da análise. Para as restantes tecnologias, a análise multicritério permitiu identificar a energia solar e a 'hydro' como as mais interessantes logo seguidas pelas eólica e geotermia.

Através do recurso a um algoritmo de series temporais foram estudadas alternativas para um sistema eléctrico baseado em 100% de energias renováveis. Tal implicaria um armazenamento dimensionado com capacidade para garantir a procura com um ciclo anual, o qual seria sobredimensionado para muitos períodos do ano e, em todo o caso, muito caro, particularmente, no caso do uso dominante de renováveis intermitentes. De fato, no caso de S. Miguel a geotermia poderá assegurar a base do diagrama o que tornará a garantia de 100% mais barata com a instalação de menos renováveis de ciclo variável. Em todo o caso, é assumido, que garantir toda a electricidade com renováveis implica maiores custos.

Na tentativa de reduzir o custo global do sistema foi considerada a hipótese de assegurar 5% da electricidade com origem em combustíveis fósseis o que, apesar de ser uma pequena percentagem se traduz em resultados expressivos. Isto mostra que os custos do sistema geral com recurso a renováveis poderão ser reduzidos substancialmente em relação ao sistema totalmente baseado nos combustíveis fósseis. Tal revelou-se ser o caso para S. Miguel.

Em conclusão, o planeamento do uso de energias renováveis até ao limite de 100% aparece como um desafio maior devido aos custos do sistema produção/distribuição associado a um armazenamento economicamente insustentável. Contudo, com relativamente pequenas contribuições dos combustíveis fósseis é possível produzir soluções competitivas. Então, para além da judiciosa selecção das energias renováveis mais adequadas, não poderão fazer esquecer a relevância das estratégias de gestão da procura também pelo uso das energias renováveis. Tal ocorre já com sistemas renováveis isolados.

II. Abstract

Socio-economic development and climate change, independently of the order, are the two major challenges for the future of sparse communities living far from Continents in hundreds of thousands remote islands around the world. Beyond the enormous challenges given the additional costs of imported fuels, remote islands face the growing restrictions to their use due to climate change constrains and the still inaccessibility of some new technologies to take advantage locally of the natural energy resources in an economic affordable manner. Yet, renewable energy sources will represent definitely the solution to overcome these challenges. Besides the innovation in technologies, that requires communitarian management approaches such as: firstly, the appropriate fine tuning of the energy needs through planning and sufficiency strategies [1] and, secondly, the overall rational energy efficiency practice down the chain from the energy source to the energy service.

In such scenario, a methodological approach to gradually cover all energy purposes that can be covered by electricity 100% renewable based is established. Energy demand scenarios considering future economic development, energy efficiency impact as well as demand side management strategies are assessed to build different scenarios under evaluation.

Following the pre-selection of renewable energy technologies fitting the resource availability and local characteristics, all potentially viable technologies undergo multi-criteria decision analysis. Technical, economic, environmental and social aspects are analyzed to identify the renewable energy sources and technologies that are most suitable for a given case. Since several criteria are considered, decision makers have the flexibility to choose supply alternatives based on their preferences and priorities, including onshore and offshore technologies.

By means of a time series algorithm a cost comparison across all scenarios is performed. The annual system costs of the selected supply technologies in combination with a storage system are investigated. For that purpose an hourly time series algorithm across the whole year is applied. The earlier defined demand over the year is now to be met with locally available renewable energy sources, so that the requirements of the storage system can be identified. Further assessments are then focused on strategies to reduce the overall system costs, whereas considerations to introduce minor contributions of fossil fuels are made. Finally, a sensitivity analysis is performed.

In the case of the island of São Miguel, Azores, a steady increase of electricity demand over time is foreseen. Two load profile types are conducted, one follows the current load profile and another is subject to load shifting measures. Several measures to shift parts of the load from peak to off-peak hours were introduced and the load shape was adjusted accordingly. In the technology pre-selection various technologies could be eliminated within each resource. Despite the resource availability, but given the regions site characteristics, some tidal energy, fixed offshore wind, most bioenergy as well as some hydro and geothermal energy technologies could be excluded from further analysis. For all remaining technologies the multi-criteria decision analysis identified solar and hydro as most favorable, followed by wind and geothermal.

By means of the time series algorithm supply alternatives based on 100% RES were built. Thereby, the storage system must compensate the demand variations that occur over the year. Hence, it is dimensioned for a yearly cycle, which makes the storage very oversized and exorbitantly expensive. The storage system is particularly oversized if high shares of variable RES are included in the supply mix. If the resource availability allows, like in the case of São Miguel, higher contributions of base load RES, e.g. geothermal, should be aimed for. In fact, a supply scenario that is based on 100% base load RES is noticeably cheaper since the storage parameters are reduced and less RES capacity is installed. Nonetheless, all alternatives based on 100% RES accumulate higher costs than a system that is based on solely fossil fuels.

An attempt was made to further reduce the overall system cost. Therefore, minor contributions of up to 5% of fossil fuels for electricity generation were allowed in the conduction of supply alternatives. Even with such a small contribution of fossil fuels the results changed noticeably. Costs of the overall system can be reduced substantially, and some alternatives reach even lower overall system costs than a system that is entirely based on fossil fuels. For São Miguel supply alternatives which are entirely or almost entirely based on base load RES present the most economical solution.

In the end, energy planning strategies towards 100% RES remain a major challenge, mainly because of the massive overall system costs and the inefficient use of an oversized storage system. However, with very small contributions of fossil fuels cost competitive solutions can be achieved. Besides the adequate selection of locally suitable RES, demand side management strategies are highly encouraged, since a greater end-user interaction provides more flexibility on the demand side to integrate high shares of RES. For isolated energy systems RES along with storage systems already present an invaluable solution for future energy planning.

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Christian

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VI. List of Abbreviations

AHP	Analytical Hierarchy Process
CdTe	Cadmium-Telluride
CF	Capacity Factor
CIGS	Copper Indium Gallium Selenide
CIS	Copper Indium Selenide
CP	Compromise Programming
CSP	Concentrating Solar Power
DM	Decision Maker
DSM	Demand Side Management
ED	Economic Dispatch
ELECTRE	Elimination and Choice Translating Reality
ESM	Energy Saving Measures
Eq.	Equation
EU	European Union
EV	Electric Vehicle
GHG	Greenhouse Gases
IC	Investment Cost
JC	Job Creation
LCoE	Levelized Cost of Electricity
LCoES	Levelized Cost of Electricity and Storage
$LCCO_2E$	Life Cycle CO_2 Emissions
LPG	Liquefied Petroleum Gas
LS	Load Shifting
LT	Lifetime
LU	Land Use
MAUT	Multi-Attribute Utility Theory
MAVT	Multi-Attribute Value Theory
MCDA	Multi-Criteria Decision Analysis
MCDA	Multi-Criteria Decision Making
Mtoe	Million tons of oil equivalents
NIMBY	Not-in-my-backyard
O&MC	Operation and Maintenance Cost
PA	Public Acceptance
PDS	Peak Demand Shifting
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PV	Photovoltaic
REL	Reliability
RES	Renewable Energy Sources
RET	Renewable Energy Technology (several RETs can be part of one RES)
RL	Regular Load
TF	Transport Fuels
TOPSIS	Technique for Order Preference by Similarity to Ideal Solutions

TWh	Terra-Watt-hours
UC	Unit Commitment
WH	Water Heaters
WP	Work Package
y	Year

VII. Nomenclature for multi-criteria decision analysis of WP3

(Chapter 4.2 p. 107 ff.):

A_r	Alternative $[r \in (1..r_{max})]$	m_q	Unnormalized criteria weights
a_{rq}	Attribute of alternative A_r and criterion c_q	$v(A_r)$	Overall value function
a_q^{max}	Highest attribute value within criterion c_q	$v_q(a_{rq})$	Value function scores of attributes
a_q^{min}	Lowest attribute value within criterion c_q	w_q	Normalized criteria weights
c_q	Criterion $[q \in (1..q_{max})]$		

VIII. Nomenclature for time series algorithm of WP4

(Chapter 3.3 p. 56 ff.):

$\boldsymbol{\alpha}$	Conversion coefficient from BTU to kWh, whereas 3,412 equals 1 kWh	$\boldsymbol{i_{su}}$	Hour at which unit n is started up
$\boldsymbol{A_{Sol}}$	Panel area	$\boldsymbol{IC}$	Specific investment cost
$\boldsymbol{A_{Sol}^{unit}}$	Unit size per kW_{el}	$\boldsymbol{inf}$	Inflation rate [2%]
$\boldsymbol{AvD_{B_{c_{j,d}}}^{FF}}$	Average fossil fuel demand of block B_c in hour j of day d	$\boldsymbol{j}$	Hour of day d
$\boldsymbol{AvD_{B_{c_{j,d}}}^{FF^*}}$	Adjusted average fossil fuel demand of block B_c in hour j of day d	$\boldsymbol{l}$	Number of unit combinations
$\boldsymbol{AvD_i^{FF^*}}$	Adjusted average fossil fuel demand in hour i	$\boldsymbol{Length_{Wav}}$	Length of wave device
$\boldsymbol{b}$	Base load RES	$\boldsymbol{LT}$	Lifetime [years]
$\boldsymbol{b_{max}}$	Maximum number of base load RES	$\boldsymbol{minG_n^{FF}}$	Generation minimum of the smallest generation unit $n = 1$
$\boldsymbol{B_c}$	Blocks within each day	$\boldsymbol{mod}$	Index for modified storage and fossil fuel generation
$\boldsymbol{Bio}$	Bioenergy	$\boldsymbol{MUT_n}$	Minimum up time of unit n
$\boldsymbol{c}$	Block count	$\boldsymbol{MDT_n}$	Minimum down time of unit n
$\boldsymbol{c_{j,d} = 1}$	Start of block count	$\boldsymbol{n}$	Unit
$\boldsymbol{c_{j,d}^{max}}$	End of block count which defines each block B_c	$\boldsymbol{O\&MC}$	Specific operation & maintenance cost
$\boldsymbol{C_{FF}}$	Cost of fossil fuels [alternative I) C_{FF} = 100 \$/MWh; alternative II) C_{FF} = 150 \$/MWh]	$\boldsymbol{P_{Wav}^{min}}$	Minimum mean wave power
$\boldsymbol{C_{ST}^{RES}}$	Cost of RES storage	$\boldsymbol{RES_b}$	Base load renewables
$\boldsymbol{C_{SP}^{RES}}$	Cost of RES spillage [1,000 \$/MWh]	$\boldsymbol{RES_v}$	Variable renewables
$\boldsymbol{C_{ST}^{FF}}$	Cost of fossil fuel storage [\$/MWh]	$\boldsymbol{\rho_{Hyd}}$	Density of water
$\boldsymbol{C_{SP}^{FF}}$	Cost of fossil fuel spillage [1,000 \$/MWh]	$\boldsymbol{ShaLos_{RES}}$	Shading losses
$\boldsymbol{C_{SU}^{FF}}$	Start-up cost [\$150]	$\boldsymbol{SOC_i^{RES\,max}}$	Highest state of charge of RES storage system
$\boldsymbol{CAP}$	Capacity	$\boldsymbol{SOC_i^{RES}}$	State of charge of RES storage system in hour i
$\boldsymbol{CAP_b^{max}}$	Defined maximum base load capacity	$\boldsymbol{SOC^{RES\,min}}$	Maximum state of charge of RES storage system
$\boldsymbol{CAP_{RES}}$	Defined RES capacity	$\boldsymbol{SOC_i^{RES\,max}}$	Minimum state of charge of RES storage system
$\boldsymbol{CAP_{RES_i}}$	Output of RES in hour i	$\boldsymbol{Sol}$	Solar
$\boldsymbol{CAP_{RES}^{Bm}}$	Defined capacity benchmark for each RES	$\boldsymbol{SP}$	Spillage
$\boldsymbol{CAP_{RES}^{max}}$	Maximum installed capacity	$\boldsymbol{SP_i^{FF}}$	Total spillage from fossil fuel in hour i
$\boldsymbol{CAP_{RES}^{min}}$	Minimum installed capacity	$\boldsymbol{SP_i^{RES}}$	Total spillage from renewables in hour i
$\boldsymbol{CAP_{RES}^{new}}$	Additionally required (new) capacity	$\boldsymbol{SP_i^{RES\,E}}$	Spillage of RES due to storage energy limits
$\boldsymbol{CAP_{RES}^{old}}$	Already installed RES capacity	$\boldsymbol{SP_i^{RES\,P}}$	Spillage of RES due to storage power limits
$\boldsymbol{CF_{RES}}$	Capacity factor of RES unit	$\boldsymbol{ST}$	Storage
$\boldsymbol{comb_l}$	Unit combination l	$\boldsymbol{ST_P^{RES}}$	Storage power of RES storage system
$\boldsymbol{d}$	Day	$\boldsymbol{ST_P^{FF}}$	Storage power of fossil fuel storage system
$\boldsymbol{D_i}$	Total demand in hour i		

Nomenclature for time series continued	
D_i^{FF}	Fossil fuel demand in hour i
$D_{j,d}^{FF}$	Fossil fuel demand in hour j of day d
dis	Discount rate for RES [7%]
Eff_{RES}	Efficiency of RES unit
Eff_{ST}^{RES}	Round-trip efficiency of RES storage system
Eff_{ST}^{FF}	Round-trip efficiency of fossil fuel storage system
$Energy\ value_{Bio}$	Energy content of feedstock
f	Variable for adjusted average fossil fuel demand
$Feed_{Bio}$	Available feedstock
FF	Fossil fuel
$Fixed\ O\&MC$	Fixed operation and maintenance cost
FL	Percentage of flexible load
FV_{Geo}	Flow volume geothermal
FV_{Hyd}	Flow volume hydro
g	Gravity
Geo	Geothermal
G_{FF_i}	Total generation from fossil fuels in hour i
$G_{FF_i}^{mod}$	Modified generation from fossil fuels in hour i
$G_{FF_i}^{P}$	Fossil fuel generation due to power limits of storage
$G_{FF_i}^{E}$	Fossil fuel generation due to energy size limits of storage
G_{RES_i}	Total RES generation in hour i
$G_{RES_{b,i}}$	Total base load generation in hour i
$G_{RES_{v,i}}$	Total variable RES load generation in hour i
$G_{ST_i}^{RES}$	Contribution of RES storage system in hour i (charging or discharging)
Hh_{Hyd}	Head height
Hyd	Hydro
i	Hour of year [h]
i_{sd}	Hour at which unit n is shut down
ST_E^{RES}	Storage energy size of RES storage system
ST_E^{FF}	Storage energy size of fossil fuel storage system
$ST_{E_i}^{CH\ RES}$	Charging of RES storage system in hour i
$ST_{E_i}^{DISCH\ RES}$	Discharging of RES storage system in hour i
$SU_{n_i}^{FF}$	Start-up of fossil fuel unit n in hour i
t	Years from now to start of project
TC	Total cost
$TD_{B_c}^{FF}$	Total fossil fuel demand for each block
ti	Total number of hours per year
TIC	Total investment cost
Tid	Tidal
$TO\&MC$	Total operation & maintenance cost
TS_{RES}	Time series for each RES
TSC	Total system cost
TSU_{FF}	Total number of start-ups for all fossil fuel units
ΔT	Temperature difference
u	Unit operation status (1 = on; 0 = off)
$units_{RES}$	Number of RES units
v	Variable RES
v_{max}	Maximum number of variable RES
$var\ O\&MC$	Variable operation and maintenance cost
Wav	Wave
Win	Wind
x_b	Variable for base load RES
x_v	Variable for variable RES
y	Variable to define initial storage level
z_P	Variable to modify storage power
z_E	Variable to modify storage energy size

1. Introduction

1.1. Context and Motivation

Access to energy is intrinsic to the human condition of living intelligent being and fulfills some basic needs, such as the preparation of food, but also all daily routines of humans, from comfort to living, i.e. transportation, propulsion, transformation/goods production, communication, mobility, housing, etc. Clearly, without access to energy life could not be at all and talking about the normal energy services, without access to clean affordable energy services nowadays type of urban life would be unthinkable. Over time humanity has explored solutions and developed technologies to convert primary energy, as it is embodied in nature, to final energy forms. While the conversion, transportation and distribution process from primary to the final energy put into the market already involves noticeable losses, it is currently the actual transformation of final energy into useful energy or actual energy services that is at the origin of the highest losses along the energy value chain. This depends, of course, on the primary energy mix of the area under consideration, i.e. a country or an island. As an illustration, for instance, for Portugal values as low as 40% of a country's primary energy[1] or even less might become useful energy or energy services, whereas the most significant energy conversion losses occur for fossil fuels due to the thermodynamics 'gooseneck' (Carnot principle) on the conversion from thermal to electric energy.

The above places a high burden on countries, regions, cities or islands, which rely on imports of primary energy forms such as oil and natural gas, which, in addition, place a great burden on a planet that is feeling the pressure of the fossil fuel driven climate change. Meanwhile renewable energies, which were used in various rudimentary natural forms for millennia (biomass for cooking and heating, solar thermal for comfort and drying, wind for pumping water and cooling, etc.), are now the subject of a wide spectrum of emerging clean technologies in the heart of the overall technological revolution of the 21st century.

Nowadays, clean or sustainable energy is a major theme in society. Sustainable development means here that the use of energy cannot imply the continuous emission of CO_2 associated to

[1] Case of Portugal in the beginning of the XXI century

[2] Oil and gas need to be upgraded or purified to a usable level. Depending on the characteristics of the extraction site, different levels of upgrading are needed. Subsequently, higher exploration and refining costs might occur.

the combustion of fossil fuels and the consequent risk of climate change expressed in the global warming [2], [3]. Fossil fuels, to be burned as they have been, cannot be part of the future. They may become a backup or a small contributor of the primary energy resources, but they will have to be substituted over the next decades.

So, the future target must be to select clean energy resources and technologies which become part of sustainable energy systems and which will be in tune with the sustainable development concept, as defined in the 1987 Brundtland report: "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* [4].

That will imply a change of the energy paradigm. Yet, in what regards the energy resources and technologies but from the start already in what regards the planning strategies understood as *"a matter of assessing the supply and demand for energy and attempting to balance them now and in the future"* [5]. That may beneficiate the wide dimension of the territory, the complementarity between geographic capabilities in terms of energy resources, and reliability of supply networks and of energy uses and, last but not least, the capacity of information technologies and systems to organize, control and manage those systems.

Islands, in their small dimension and large distance from the mainland or other islands, separated by the ocean quite rough sometimes and challenged with the frightening rising water level, are facing the most crucial challenges. Islands need to maintain their population with a modern life level and for that they must be ready to welcome visitors and provide appropriate and attractive touristic conditions. That implies a diversity of energy services with some eventual seasonal peaks and some demanding guests independent of the momentaneous climate conditions. So islands are very critical energy cases in the context of our world of today and regarding the future challenges, namely the global warming, i.e. the climate change consequences. The signs of climate change are clearly noticeable, since the sea level is rising and several islands and island states, mainly in the Pacific Ocean, are foreseen to disappear in the near future. Otherwise, islands are also confronted with major challenges concerning the supply of energy.

The importance of energy planning strategies to achieve targets such as the reduction of greenhouse gas (GHG) emissions through more efficient use and management of energy sources or more renewable energy sources penetration, not only on the supply but also on the demand side, clarifies why for instance the European Union (EU) set very strict and binding energy targets [6], [7], [8]. Yet, further continuous improvements and adjustments in policies and action plans are required. Therefore, studies of the new energy paradigm are essential to support decision makers [9].

It is estimated that there are approximately 180,000 inhabited islands around the world, whereas only a small share of those is connected to the mainland power system. Within the European Union (EU) 286 inhabited islands can be found, composing around 2% of the EU´s population [10].

Since islands are most regularly dependent on fossil fuel imports, the economic capabilities of islands are determining factors for the amount of energy that can be afforded. The European Island Agenda already highlighted two decades ago that *"non-renewable energy sources are provisional solutions, inadequate to solve in the long-term the energy problems of the islands"* [11]. Hence, islands with limited financial assets strive to define the essential energy needs. Thereby, energy sufficiency, as proposed by the International Energy Agency [12], should be the primer energy strategy, followed by energy efficiency and, more and more, renewable energy sources. This implies that alternatives to reduce the energy needs must be explored in the first instance. Then measures to reduce energy consumption can be explored. Finally, after the final energy needs are re-defined renewable energies may be introduced to cover all energy needs. All three measures also contribute to reduce CO_2 emissions and combat climate change.

Various islands have already proclaimed to cover 100% of their electricity needs from renewable energy sources (RES) (e.g. Samsoe (Denmark), El Hierro (Canary Islands - Spain) or Gotland (Sweden)). Yet, it should be noticed that electricity has been covering only around 1/3 of the final energy services; the remainder being heat and transport fuels (TF). Since this trend is changing and renewable energies in their diverse forms can be used to cover all energy services, the concurrent planning aspects should aim to increase the share of renewables on the total primary energy demand. Thereby, electricity will have a particular role, since it can be used to cover all energy services.

Due to their distinct settings and challenges, islands present adequate research cases to apply and envision new planning concepts. In this research a comprehensive strategic energy planning model is developed to support decision makers in the transition towards a future energy system dominated by RES based electricity. High shares of indigenous energy sources shall be targeted, since they represent long-term and sustainable solutions [13] and confront the energy challenges on islands.

For application of the research methodologies one island of the Azores archipelago is proposed. The Azores is a Portuguese territory in the Northern hemisphere of the Atlantic Ocean almost half way between two continents: Europe (Iberian Peninsula) and North America. The archipelago offers nine quite apart and diverse islands with great need and potential to apply energy planning research. Just to mention there are cases of islands that face periods with very rough sea which places issues of supply and storage of fuels. The Azores´ economic strength and comprehensive institutional infrastructures allow the islands to be a role model for many other island(s) (states) to which the herein proposed research practices can then be transferred to.

The outline of this research is clustered in 7 Chapters. Following the introduction in Chapter 1, the research sets out to undertake a literature review focused on the energy planning aspects of concern for islands in Chapter 2. In Chapter 3 the proposed methodological approach is presented. The decision support for technology selection is then described in Chapter 4. For both chapters illustrative examples from the European and North American contexts are incorporated. The proposed concept can then be applied to any island or isolated energy system. Due to the fact that energy prices and commodities are usually given and traded in US$ all herein undertaken calculations are performed in US$.

After characterizing the Azores´ energy portfolio, Chapter 5 provides context for one selected island: São Miguel. The entire concept is then applied to São Miguel for which results are presented. Conclusions are presented in Chapter 6, while in Chapter 7 suggestions for future work are listed.

1.2. Problem Definition

Islands are generally confronted by a great variety of energy challenges. They may range from socio-economic and environmental to technological challenges, with the major challenges being the high reliance on fossil fuel imports and the need to face the effects of climate change from the energy perspective and in some cases from the survival perspective, meaning due to the rising sea water levels. Given the natural conditions of an island there are usually spatial limitations (due to their dimension and specific restrictions of natural heritage or conservation sites) and no grid-connections to the mainland.

The great diversity of energy challenges makes islands an interesting place for field studies. While new energy planning strategies can change the current system for a better one, it is largely a challenge of interacting with a variety of (mainly local) stakeholders. On the one hand side, a conservative mentality might oppose or prevent the implementation of new strategies and technologies [14]. Different studies revealed that aspects related to 'not-in-my-backyard' (NIMBY) should not be underestimated, since they can prevent the implementation of a wide range of technologies or large projects on islands [15], [16], [17]. On the other side, it is the small size of islands and the limited population that also presents a great opportunity to introduce new ideas and concepts.

The major economic sectors and the dominating day-to-day business and industry activities on islands are mostly tourism, fishing and/or a few site-specific industries [18], [19]. Especially tourism causes the energy demand to fluctuate significantly between the seasons and holidays [20], [21], whereby the major challenge lies in providing adequate energy during the peak summer season [22]. In correlation with tourism there is often also a high variation in the number of island inhabitants [20], which during the main season might exceed that of the off-peak season by a few times [23].

From the technological viewpoint security of supply has to be considered as another major planning challenge, especially when dealing with a high penetration of renewable energy sources (RES). The high variability of some renewables (mainly PV, wind, wave and tidal) puts a lot of constraints on the operation of the system. On the socio-economic side the lack of specialized work force and the high reliance on specific industry sectors may be considerable challenges. Further energy challenges on islands are presented in Figure 1-1.

To guarantee energy supply for isolated systems based on high shares of RES, the energy system will require substantial access and backup capacity (energy storage solutions). For the latter, storage systems such as hydrogen, flywheels, batteries, electric vehicles or even hydro-storage power plants may be considered as alternative to fast responding thermal units [24], [25], [26]. The importance of storage systems is highlighted by the fact that variable RES such as Photovoltaic (PV) or wind, can only cover around 30% of the energy demand without adequate backup [27], [28]. In the end, supply needs to meet demand at all times, even in those peak periods, which might only occur for a few hours or days per year [29].

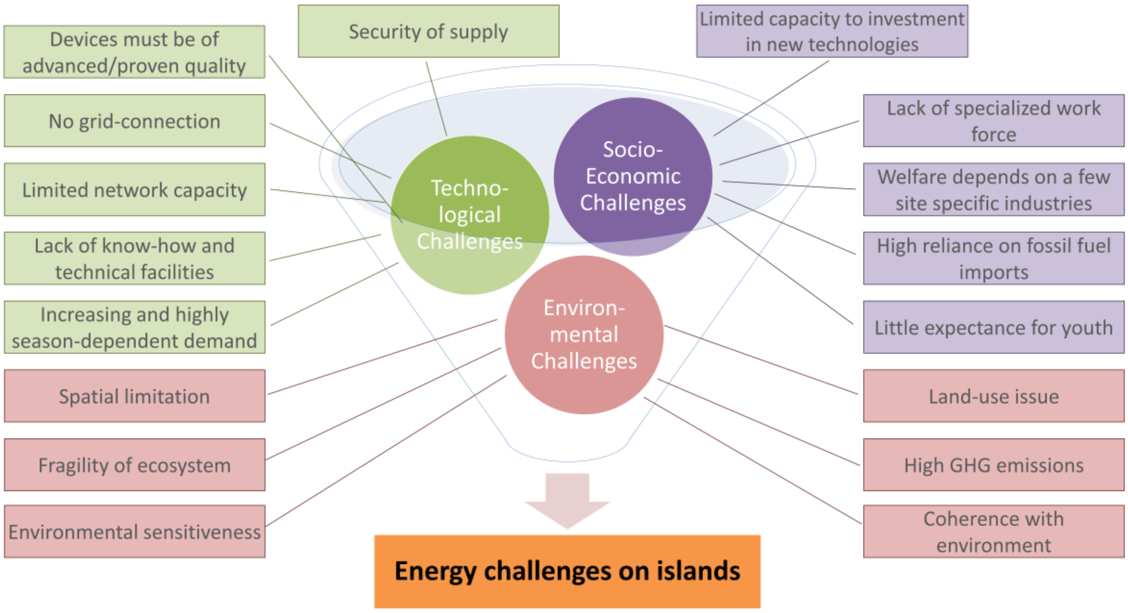


Figure 1-1: Technological, socio-economic and environmental challenges on islands

Within this research the Azores islands are selected for investigation. Because of the long distance (almost 1,400 km) to the nearest mainland, the reliance on energy imports for the 246,000 inhabitants of the archipelago is immense and expensive [10], [30], [31]. Without the subsidies from the Portuguese mainland the prices for the islands inhabitants might be much, if not even several times, higher. In 2008 the total primary energy demand was 15,562.62 TJ. 40% of that went into electricity generation. Only 5.6% were used in the industry. The remainder (over 50%) was used for different means of transportation (road, plane, sea). At the same time, the contribution of RES on primary energy consumption was 13% and that for renewables based electricity 28% respectively [32], [33], [34]. Trying to become independent from or at least lower fossil fuel imports is crucial; especially as oil derivatives cannot be delivered on a daily basis and need to be stored for several weeks or months. This form of energy supply comes at a very high price, for which reason the introduction of demand side measures along with alternative technologies represent an excellent test study [35], [36], [37], [38], [39].

1.3. Research Questions

In order to evaluate an increasing RES based electricity supply in the overall energy system and to overcome the energy supply challenges while safeguarding the planets sustainability, the selection of possible RES solutions is based on a set of conditions and criteria. Primarily, technologies are pre-selected based on resource availability and local site characteristics. Only chosen technologies will then be assessed under technical, economic, environmental and social aspects so that decision makers may identify the most appropriate technologies for their case.

The following research questions are investigated:

1. How to identify and quantify the electricity needs of a given island bearing in mind the technological, environmental and socio-economic criteria context?
2. How to introduce a large share of RES considering the technological options and the economic capabilities and limitations of an island electricity system?
3. How to develop an electricity planning model that allows to compare scenarios and solutions across various time-horizons, including price developments, for multiple renewable energy sources?

The hypotheses for this research are the following:

1. In the long-term it is reasonable to achieve all-purpose electricity from renewable energies, whereas a large share could even come from offshore RES.
2. Energy sufficiency and energy efficiency are essential parts of energy planning within the new paradigm. While several measures to re-define and reduce demand can be introduced, a comprehensive energy vector shift from transport fuels and heat to electricity might eventually increase demand beyond the expected savings.

1.4. Objectives

Energy sectors are clustered in domestic, commercial, both focused on buildings and building dominated activities, industry and transport. They all involve several energy carriers: electricity, heat or fuel derivatives for transport.

The major objective of this research is to develop an energy planning model for isolated islands to increase the share of electricity from renewable sources in the overall energy system. The concept will provide a holistic solution that considers the current situation and plans for a future system that covers all energy services that might or can become electric with indigenous sources. A sustainability assessment is used to pre-select technologies. By means of a time series algorithm the energy supply for each scenario shall be evaluated. The model may be applied by (island) decision makers or energy agencies and should support them in their strategic decision making. While Gasparatos and Scolobig divide sustainable assessment tools in monetary, biophysical and indicator tools [40], this research incorporates aspects of all three tools in one integrated planning model.

This research also aims at providing an evaluation of how the criteria of sustainability along with the demand development will change the decision for or against certain technologies over time. Special consideration is given to the development of offshore technologies as well as the scenarios and conditions under which offshore renewable energy technologies become attractive to be used within an island energy system. In the end, it is aimed to identify locally suitable and sustainable renewable energy and storage solutions to gradually cover all energy services of an island within 10-30 years' time. Therefore, a time series algorithm is built to compare various supply alternatives and scenarios from an economic viewpoint. Thus, it is expected that the algorithm demonstrates the sequential changes in terms of the quantity of each RES selected along with the required size of the storage system.

2. State of the art

Chapter 2 presents an overview of the energy planning problematic and procedures for isolated islands. This includes a review on energy demand, a breakdown and development trends of energy demand, reduction and saving potentials, planning aspects, selection criteria for renewable energy and storage technologies, sustainability assessments and multi-criteria decision analysis. The initial section aims to clarify the terminology as it appears to be quite often an obstacle to the promotion of changes in the energy world as the nomenclature and terminology tend to be marked by the professionals and practitioners of a particular energy form. After providing understanding about energy, energy vectors and RES accounting this chapter closes with a summary of gaps that were identified in the literature review.

2.1. Energy vectors and renewables accounting

Oil, gas, coal and uranium are all exhaustible primary energy sources that will be depleted at a certain moment in time. Without further transformation[2] these sources (apart from nuclear) can be used for heating, cooling, hot water, propulsion or industry purposes (Figure 2-1). Hence, they provide heat and/or transport fuels. While this was enough to satisfy the energy needs some centuries ago, the rapid industrialization and increasing permeation of technology in modern society has called for another energy vector: electricity.

Electricity is proficient to cover all our energy services, e.g. lighting, ventilation, multimedia and all the above mentioned. Since all fossil fuel energy sources can also be transformed into electricity, its flexibility in use is a major benefit compared to the pre-defined energy uses that can be covered from heat and transport fuels.

Remarkably human beings have taken advantage of RES for millennia; not for electricity generation but for a variety of other purposes, such as biomass for heating and cooking, hydro for propulsion, solar for drying and wind for ventilation and cooling. Only in the last two centuries and driven by innovation and entrepreneurship, electricity has become a major part of energy demand. On the renewables side hydro power generation dates back to the 1880´s,

[2] Oil and gas need to be upgraded or purified to a usable level. Depending on the characteristics of the extraction site, different levels of upgrading are needed. Subsequently, higher exploration and refining costs might occur.

but it is only a few decades that wind, PV and other renewables are being used on a commercial scale.

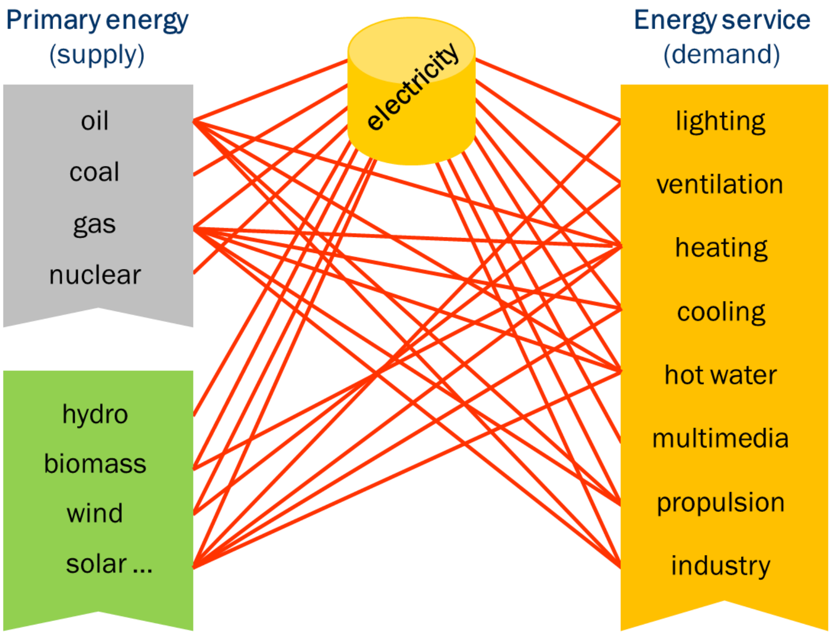


Figure 2-1: Electricity the queen of the energy vectors [41]

Because of the capability to generate electricity from abundant resources, nowadays RES can be used to reduce, and in combination with storage systems even vanish, the contribution of fossil fuels in the energy mix. Besides, who knows if by 2030 humans will be able to control and use hydrogen or fusion technologies?

The use of renewables bears another major benefit, which can be described best with the way renewables are accounted for in the primary energy balance. While the zero equivalent method does not account electricity generation from RES in the primary energy balance, the technical conversion efficiency method uses the actual technology specific efficiencies to account RES in primary energy balances. In between these two “extreme” accounting methods, three other methods with varying degrees of RES accounting are considered. All methods for RES accounting are summarized in Table 2-1.

Numerical descriptions for each of the 5 accounting methods are presented in Table 2-2. According to the direct equivalent or physical energy content methods, which are already used by leading international organizations, the value of supplying electricity from RES becomes emphasized. In fact, the high conversion losses that occur during the transformation from fossil fuels into electricity can be avoided.

Table 2-1: Accounting methods for renewables in primary energy consumption [42]

Method	Description
Zero equivalent method	Account no primary energy for electricity generation (1 MJ of electricity from wind equals 0 MJ of primary energy)
Direct equivalent method	Primary energy equivalence of 100% between primary energy and electricity is used (1 MJ of electricity from wind equals 1 MJ of primary energy)
Physical energy method	- Primary energy *"should be the first energy form downstream in the production process for which multiple energy uses are practical"* - The first practical use of wind, hydro, etc. is electricity itself (100% efficiency is assumed)
Substitution method	- Primary energy is "*energy in the form that it is first accounted for in a statistical energy balance, before any transformation"* - *"to avoid challenges of determining technical conversion efficiencies of renewable energy sources, conversion efficiencies of fossil fuel plants that were substituted by the electricity from renewable energies or that would be required to replace the electricity"*
Technical conversion efficiencies	- Calculates technical conversion efficiency for electricity generation according to standard; e.g. VDI standard 4600 - Primary energy is the "*energy content of energy carriers that have not yet been subjected to any conversion"*

Table 2-2: Primary energy equivalents and conversion efficiencies for electricity generation (gross production) of renewable energy sources (Adapted based on [42])

Energy Source	Zero equivalent method	Direct equivalent method (as applied by UN statistics)	Physical energy content method (as applied by Eurostat and IEA)	Substitution method (as applied by US EIA)	Technical conversion efficiency (as applied in LCA databases)
Hydro	n.a.	100%	100%	39.7% [3]	85%
Wind	n.a.	100%	100%	39.7% [3]	40%
Solar (PV)	n.a.	100%	100%	39.7% [3]	13.4%
Solar (thermal electric	n.a.	100%	33%	39.7% [3]	12.4%
Geothermal	n.a.	100%	10%	39.7% [3]	22.4%
Biomass	n.a.	28.6% [1]			
Biomass & bioliquids	n.a.	26.2% [1]			
Waste	n.a.	17.7% [2]			
Nuclear	n.a.	100%	33%	33%	33%
Imported electricity	n.a.	100%	100%	100%	source and country specific

[1] average European gross efficiency for biomass powered electricity plants (IEA 2012B), reference year 2010
[2] average European gross efficiency for municipal solid waste incinerators, producing electricity only (CEWEP 2012)
[3] substitution via average European fossil power plant for non-combustible renewable energy sources (gross efficiency), calculated by PE International based on IEA (2012B), reference year 2010

2.2. Energy demand side considerations

While in the past energy supply had to follow demand, in the new energy paradigm the roles have changed, and at times, demand can follow supply. This research starts elaborating from the demand side and provides a breakdown of energy consumption by sector and fuel. Then, energy services are analyzed and the potentials for shifting thermal and transportation services into electric ones are assessed. Thereafter, the need for energy sufficiency is discussed, before energy efficiency potentials are explored and typical consumption patterns are addressed.

2.2.1. Breakdown of energy consumption by fuel and sector

When assessing the current energy demand by fuel and by sector, for most European countries the share of fossil fuels is high in all sectors[3] [43]. More importantly, the reliance on fossil fuels is expected to remain very high even beyond 2030 [44], [45]. This is mainly due to the purpose we use energy. Based on the nature of required processes and services, different energy sources are needed. While the transportation sector is dominated by almost exclusively oil, natural gas is the main source for thermal needs within the residential/commercial and industry sector [46]. According to [45] and [47] electricity can be considered as another sector. Thereby, one will see that electricity generation is also dominated by fossil fuels. Within the European Union there is a high share of coal and nuclear power. Apart from hydro power, other RES are only scarcely contributing yet [43].

The energy supply of most non-grid connected islands[4] is even more dominated by fossil fuels [48]. However, the breakdown of energy consumption by sector shows usually a considerably lower demand for the industry sector, mainly because energy intensive industries (e.g. cement, iron, chemical, paper, etc.) do not exist on islands.[5] Moreover, the electricity generation is dominated by oil derivatives which are converted in expensive diesel engines [49]. A broad variety of research works has been studied to better understand the energy flows from primary to final energy and the energy vectors that are required within each sector [50], [51], [52]. These studies are then used to support the methodological part of energy flows which is discussed in Chapter 3.2 (p. 35 ff.).

[3] Sectors are generally divided in residential, commercial, industry and transport
[4] These islands have their own network and generation capacity.
[5] Due to the lack of energy intensive industries on islands, service shifts within the transportation, residential and commercial sector will be analyzed predominately. Indeed, it seems more uncertain to define specific shifting potentials for the industry, as the energy requirements and carriers are determined by the product of the industry sector respectively [402].

2.2.2. Energy services

Moving on along the energy value chain, the final energy demand by sector now can be broken down into different services or end-uses. An overview of end-uses by sector is presented in Table 2-3 [53], [54], [55]. The applicable and dominating energy vector(s) for each service within the residential/commercial and transport sector are indicated.

Table 2-3: Classification of services by sector

Sector	Residential & Commercial	Industry	Transport
Services	Space heating (H*, E)	Process heating	Cars (TF*, E)
	Water heating (H*, E)	Process cooling/refrigeration	Trucks and light vehicles (TF*, E)
	Electric appliances (E*)	Other process uses	Air (TF*)
	Lighting (E*)	Electro-chemical	Rail (TF*, E)
	Air conditioning (E*)	Machine drive	Water (TF*)
	Cooking (H*, E)	Facility HVAC	Bus and motorcycles (TF*, E)
		Lighting	
		Other facility support	
		Onsite transportation	
		Other non-process	
E = electricity; H = heat; TF = transport fuels; * = dominating energy vector			

Both, heat and transport fuels can be provided from specific renewable energy technologies. Thermal RETs include solar thermal panels, ground source heat pumps or stoves heated with biomass [56], [57], [58], [59]. Similarly, transport fuels can be provided from biofuels [60], [61], [62]. Yet, the contribution of heat and transport fuels based on RES is low.

In order to increase the contribution of RES across all sectors and services, the next step can be the coverage of some heat and transport fuel requirements from RES based electricity. While no significant study for shifting thermal needs to electric ones could be found, in the transport sector it is already planned to gradually increase the share of electric vehicles [63]. Peças Lopes et al. [64] and Richardson [65] conducted studies about the integration of electric vehicles in power systems. Borba et al. [66] and Dallinger et al. [67] analyzed how electric vehicles can contribute to increase the share of variable RES in power systems.

On the one hand, Baptista et al. state that it seems inappropriate to achieve 100% electrical based transportation services within the foreseeable future [68]. Only around 20% of purely electrical vehicles are predicted by 2050 for the island of Flores, Azores. 10% remain diesel and gasoline powered, and the remaining 70% are combinations of hybrid and plug-in electric vehicles with gasoline and diesel.

On the other hand, there is great potential to cover major parts of the thermal requirements, namely space and water heating along with cooking, in the residential and commercial sector with electricity[6]. Available appliances by end-use include:

- Space heating: heat pumps, fans, radiators, night store heaters or underfloor heaters
- Water heating: immediate water heaters (WH), storage WH or low capacity WH
- Cooking: electric oven, cooker, kettle or hubs

2.2.3. Energy sufficiency

According to the International Energy Agency energy sufficiency is the primer energy strategy towards environmental sustainability. Prior to the implementation of energy saving measures and before the introduction of renewable energy systems it is essential to reduce the energy needs to the essential ones, thus keeping the required comfort level [12]. Sufficiency measures do not look at the design or the operation and management of an object, but rather its broader environmental context. In the case of buildings this includes the *"orientation vis-a-vis the sun, its placement with respect to surroundings, daylight and sunshine requirements based on bio-climatic design principles"* among others [12]. Further aspects of energy sufficiency include, but are not limited to: temperature set points for heating, cooling and hot water; use of public transportation or the change of transport vehicles (e.g. taking a train for short distances rather than a flight or sending shipments via train/ships instead of road vehicles).

The combined effects of energy sufficiency bear great potential to reduce energy demand. Even a comparison of the per capita energy consumption provides good indication that reductions can be achieved without significant losses in comfort. For instance, in 2014 the average toe per capita in the United States was around 6.8, whereas in Germany only 3.8 toe per capita were used[7] [69]. As a matter of fact, a widespread and strict implementation of energy sufficiency plans can help substantially in redefining the essential energy needs per capita. The accumulated savings can then greatly contribute towards sustainable development.

[6] This statement considers a Mediterranean climate. Obviously, in cooler climates (e.g. Northern Europe) heating demand is very high. Heating based on only electricity would be very cost-intensive. Also, heat generating RETs (mainly biomass but also solar thermal or ground source heat pumps) could be considered. However, such systems will not be analyzed nor incorporated in this research. Consequently, further elaborations are excluded from this literature review and research.

[7] For the comparison two leading economies in the world were used, which have similar climatic conditions and where habitants value the level of comfort a lot. Still, there are significant consumption differences, which are partially driven by the sufficient use of energy.

2.2.4. Consumption pattern and measures to reduce and shift demand

The new energy paradigm highlights the influence of the demand side. While demand and supply can change significantly throughout the year, season or over the day and peak electricity demand might only occur for a few minutes or hours per year [29], [70], [71], behavioral changes and flexible end-uses can decrease the maximum peak substantially [72]. Indeed, demand shifts need to be considered to smoothen and reduce the peaks [73]. According to [74], typical techniques include peak clipping, conservation, load building, valley filling, load shifting and flexible load shape. Several other behavioral and policy measures have been studied. Abaravicius [75] focused on reducing peak load via customer flexibility. Though, the results demonstrate that customer´s electrical expenses need to be reduced to improve consumption patterns. Breukers et al. [76] developed a toolbox to improve energy demand side management (DSM). The tool should help intermediaries in planning and implementing energy DSM projects. Within their work it was found that behavioral changes must fit into context to be durable. With carefully designed demand side policies significant peak capacity reductions are achievable [77].

Especially for islands in warm climates, alternatives to reduce the peak are vital during hot summer days, when tourism and cooling demand are high [23]. In order to provide energy security it is important, that both, the peak as well as annual demand will be smoothened, balanced and reduced [29], [78], [79]. A wide energy portfolio based on various resources can reduce some of the insecurity that is caused by fluctuating RES [80]. This accounts especially for the more reliable and predictable hydro, geothermal, biomass and tidal energy resources [81], [82], [83], [84], but also for storage technologies.

2.3. Electricity based on renewable energy sources

Even though the variety of renewable energy technologies (RETs) to generate electricity is steadily increasing, the RES remain the same. Sources can be divided in: Biomass, Geothermal, Hydrogen, Hydropower, Ocean Power (wave, tidal and thermal gradient), Solar Energy and Wind. While biomass, geothermal, solar and thermal gradient can generate heat and electricity respectively (and biomass even transport fuels), all other sources solely generate electricity.

Since this research focuses on the provision of electricity, the following paragraphs highlight each source according to its contribution in the global power generation mix [85], [86]. Each technology is classified according to the load(s) it can cover. The considered loads include: base load, intermediate load, peak load and must-take load (Table 2-4).

Table 2-4: Description of load types (Adapted based on [87])

Generator type	Description	Examples
Base load	Provides a constant rate of production	Biomass; Geothermal; Hydropower
Intermediate load	Varies production according to demand and/or has a predictable availability	CSP with storage [2]; Hydropower; Tidal and wave energy
Peak load	Provides power during peak demand and/or ramps up and down very quickly	PV, CSP [1]and pump-storage
Must-take load	Is dependent on the variable source which should be “taken” when available	CSP w/o storage; PV; Wind

CSP = Concentrating Solar Power; PV = Photovoltaic

[1] Although they do not meet the rapid response requirements of peaking generators, solar PV and CSP generation coincide with summer demand peaks caused by air-conditioning loads, especially in the sunny southwest.

[2] With sufficient thermal energy storage, CSP plants can run as base load generators. The US Dept. of Energy is funding research to explore base load CSP systems.

Hydropower is certainly the most applied and mature RES. In principle hydro energy is indirectly solar energy, which converts flowing water (kinetic energy) from heights (potential) via a turbine and generator into electrical energy [88]. Depending on the head height (the difference between two water levels) and the flow volume different turbines are used [89], [90]. Hydropower is divided into run-of-the-river, conventional and pump-storage applications. While run-of-the-river plants are a base to intermediate load technology, pump-storage plants are peak load applications [91]. Conventional stations, which utilize damned water, can be considered as an intermediate load, especially when they are season dependent [91]. Because of the natural and spatial limitation, large hydro power stations are less likely to be implemented in small island systems.

Wind energy is kinetic energy that is converted from solar energy. The turbine blades extract energy from moving air, which is caused by temperature differences. The rotational movement of the blades causes a generator to run (mechanical energy) and to generate electricity. More importantly, wind power is proportional to the cube of the wind speed [92]. As a result of its high fluctuations wind energy is very variable. Hence, it is a must-take load that requires sufficient backup capacity [87]. The most common configuration, the “Danish concept”, uses a horizontal axis tree bladed rotor. It follows an upwind orientation and customs a yaw system to keep the rotor blades in the wind [93].

Biomass makes use of the energy from the sun that is stored within organic matter. By breaking down the biomass source, energy is released [94]. Procedures to generate electricity include direct combustion, gasification, co-firing and anaerobic digestions [95]. Most processes also create a significant amount of heat. In the context of spatial limitation, like on islands, it is arguable whether biomass energy crops compete with agriculture space for food crops [96]. Even though biomass can be a very predictable and constant energy supplier to cover base loads [87], the issue of food versus feedstock should be assessed when considering biomass as supply alternative. Thus, under limited land availability biomass may be used as peak-load power plant only, whereas the biomass is utilized to fire gas turbines [97].

Solar energy technologies use sunlight directly to convert it into electricity [98], [99]. While Photovoltaic (PV) systems can be scaled very small (micro and mini systems), concentrating solar power (CSP) appliances are dimensioned on a large scale[8]. Similar as wind energy, solar energy is very variable, for which reason appropriate backup capacities are required. At the same time, PV systems work during the day, when the load is high. Therefore, PV can be considered, both, as must-take and peak load [87].

Geothermal technologies use the energy that is stored within the earth. Depending on the temperature level geothermal technologies can either be used for heating or to generate electricity from thermal energy. For the latter, high temperatures (above 110 degree Celsius) or specific binary plants (Rankine or Kalina-cycle) are required [100]. One of the major advantages is the nearly constant power output geothermal technologies possess [101].

Since oceans cover more than 70% of the planet's surface [102], marine energy possesses an immense potential [103]. Yet, the contribution of offshore technologies is insignificant. Only fixed offshore wind has been fully developed and can be considered as mature [104]. In contrast to onshore wind a higher capacity factor can be reached at sea [105], which also leads to a higher dispatch. Nonetheless, offshore wind can only be considered as must-take or intermediate load that requires adequate backup capacity. For wave and tidal technologies no dominant concept has emerged yet [106], [107]. Tidal stream appliances work similar as wind turbines, though they extract their movement (kinetic energy) from the water to drive a generator and convert energy into electricity [108]. Due to its regular occurrence tidal energy can be used as intermediate load. In contrast, wave energy is the result of wind that hits the surface of the sea and generates movement. The mechanical energy can then be converted into electrical energy [109]. Even though waves occur very regularly, the significant wave height and the mean wave period, both factors that determine the power output, vary significantly over the day and year [110]. Therefore, waves need to be classified as must-take or intermediate loads that require backup capacity. Because of the high research and development efforts it seems reasonable to achieve considerable shares of ocean based

[8] Due the space requirements and the low market maturity concentrated solar power plants, part from parabolic trough, will not be further assessed within this research.

electricity within the next 30 years, especially in technology developing countries such as the UK or Japan, but also on smaller islands that are subject to high electricity prices [111].

The last resource is hydrogen. Once extracted to its pure form, hydrogen (chemical energy) can be used in a fuel cell to generate electricity. The element is found in various organic compounds, mainly hydrocarbons. It can be separated via a reforming process or electrolysis [112]. Due to its early stage development status, hydrogen is still negligible in any energy mix. However, there is potential to use hydrogen as storage device to balance the system. Plus, its flexibility and various production paths allow using hydrogen as base, intermediate or even peak load. Several studies, combining hydrogen with hydroelectricity, wind or PV have been conducted [112], [113].

Even though nearly all renewable energy technologies face financial challenges [114] the learning curves are rapidly improving. This is in particular the case for wind and PV which have experienced drastic price declines in the last few decades [115], [116], [117]; and more importantly, further reductions are expected. Similar trends are also anticipated for offshore technologies which might become of particular interest for islands in the upcoming decades [118], [119], [120]. Besides their vast energy resource potentials, offshore RES eliminate the spatial limitations [121], [122], [123] and accessibility challenges that are often crucial on islands [124]. Especially, in heritage or environmentally protected areas the NIMBY issue is not negligible [15], [16], [17].

2.4. Planning aspects with renewables

The natural occurrence of RES is a key driver for the amount of RES that can be integrated in an energy system. Even though PV and wind are very variable energy sources [125], [126], [127], they are widely implemented and strongly growing nowadays [128], [129]. The main drawback of having a large share of PV and wind lies in matching demand and supply [101], [130], since the higher penetration of fluctuating RES causes a shift towards more peak load capacity and less base load capacity [131]. In contrary, biomass[9], geothermal or hydro[10] power could be used as base and/or intermediate loads [131], [87], [113]. These RES are very predictable and they can be easily integrated in the network [132], [133].

Since a secure operation of the electricity network requires very strict rules and procedures, different measures to balance demand and supply at any instant must be applied. The variability and uncertainty of highly variable resources affect the grid at every level (from local to regional and national) and at any time scale [134]. The focus within this research is placed on hours, days, months and eventually years; mainly because this research represents a strategic long-term planning concept. Various real-time related control actions are presented henceforth, whereas procedures for seconds and minutes are not considered in this work.

- Seconds – power quality, system fault
- Minutes – regulation
- Hours – system dispatch
- Days – unit commitment
- Months – mid-term planning and maintenance scheduling
- Years – capacity planning of generation and transmission

Despite the fact that on the mainland the network can easier adjust to fluctuations by ramping up or down power plants, mainly combined-cycle gas turbines or even pump-storage plants [135], [136], for isolated systems this presents a substantial challenge [10]. Forecasting of RES is nowadays a key input for these issues [137]. If security of supply is the main criteria for a reliable system then well-defined energy management strategies (including demand (load) shifts), energy backup plans and/or storage systems are required [138], [139], [140]. These considerations become even more vital when planning towards very high penetration levels of renewables [10].

[9] In some cases it is also used as peak load [97].
[10] Hydropower in the form of pumped-storage can be another form of peak load. Since it is flexible, it can be used to balance variable sources such as wind and PV.

2.5. Electricity storage technologies

Despite having an energy system with very high shares of RES, demand needs to be covered at all times. Consequently, storage systems are required that can respond to shortages in peak, intermediate or even base load.

Electricity storage technologies can be classified according to the a) technical maturity of different technologies, b) energy transformation process, c) functionality methods, d) services that technology delivers to the power system, e) discharge duration and power rating or f) others [141], [142] (Figure 2-2).

Even though storage systems experience continuous market deployment, they are still very expensive and/or at an early development stage [26], [143], [144]. Hence, costs can be saved by designing energy systems with a low storage system capacity and energy size.

Due to its power rating and discharge duration pumped hydro storage seems the most adequate storage system for this research, especially if very high shares of variable RES shall be integrated. Then it is essential to provide large amounts of storage power instantly or store energy over longer periods. In case, very high shares of base load RES are installed, the storage system is more likely to charge and discharge on a daily basis, whereas batteries such as Lithium-Ion batteries could also be applied.

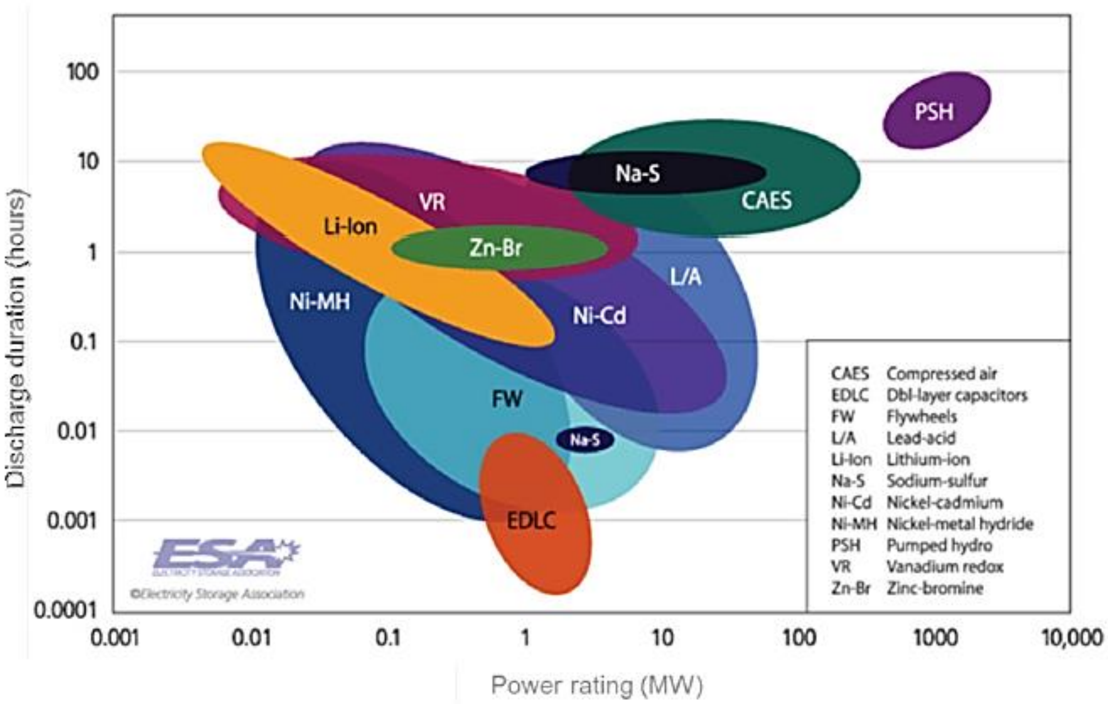


Figure 2-2: Categorization of storage systems by discharge duration and power rating [142]

2.6. Energy planning – Matching demand and supply

The imperative of energy planning is to dynamically match demand and supply. Thereby, the determination of grid-connected or off-grid systems represents a major aspect for designing the energy system.

Various energy planning tools have been created over the decades [145]. The goals, strategies, scales, etc. they follow and apply are equally diverse. For the purpose of this research only tools that are capable of simulating solutions with 100% RES were analyzed (Table 2-5). Each tool has been assessed in terms of its goal, whereas differentiations in investment, optimization and simulation are made. The scale is another important factor. It provides indirectly context about the system size, potential interconnectivities and possibilities of backup. Lastly, the inclusion of offshore technologies and storage systems in the different tools was evaluated, since both shall be considered within the planning concept of this research.[11]

Table 2-5: Energy planning tools with 100% RES based electricity

Tool	Description	Goal	Scale	Offshore	Storage
E4cast * [146]	Simulate future energy needs and how to meet them	I.	N./R.	-	-
EMPS [147]	Analyses hydro power in power systems	S./O./I.	N./R.	-	✓
EnergyPLAN * [148], [149], [150], [151]	Design national and regional energy planning strategies considering the overall energy-system	S./O./I.	N./R.	✓	✓
energyPRO * [152], [153]	Combined techno-economic design, analysis, and optimization	S./O./I.	P./R.	-	✓
H_2RES [125], [132]	Simulate integration of RES in energy systems	S./O.	Island	✓ (W)	✓
Homer [154], [155]	Optimizes stand-alone & grid-connected power systems	S./O./I.	L.	-	✓
INFORSE * [156]	Balancing tool for national energy systems	S.	N./R.	✓ (W)	-
Invert * [157]	Design of efficient promotion schemes for RES	I.	N./R.	-	-
LEAP * [158]	Analyze national energy systems	S.	N./R.	-	-
Mesap PlaNet * [159]	Calculates energy and emission balances	S.	N./R.	-	✓
MiniCAM [160], [161]	Examine changes in global & regional energy systems	S.	G./R.	-	-
PERSEUS [162]	Energy and material flow tool	I.	In.	✓	✓
ProdRisk [163]	Optimization and simulation of hydro-thermal systems	O.	N./R.	-	✓
RETScreen [164], [165]	Decision support tool that evaluates energy aspects	I.	Any	✓	✓
SimREN * [166]	Design supply-demand tools	S.	N./R.	-	✓
SIVAEL [145]	Power system simulation related to CHP	S./O.	N./R.	-	✓

Goal: I. = Investment; O. = Optimization; S. = Simulation
Scale: G. = Global; IN. = International; N. = National; R. = Regional; L. = Local; P. = Project specific
Offshore (W = Wave and T = Tidal) and **storage technologies** considered: yes [✓] or no [-]
* In these tools scenarios of 100% renewables have already been applied.

The review[12] clearly highlights the lack of research in offshore technologies and island (or isolated) energy systems. Brief descriptions of the above listed and other tools dealing with the integration of RES into various energy systems were conducted by [48], [145], [167].

[11] While the focus of energy planning tools was placed on offshore technologies and storage systems, that does not imply that other RES are not considered in this work. In contrary, the inclusion of offshore technologies seems encouraging to increase supply alternatives beyond the already established onshore RES.
[12] Review undertaken by the end of 2013

In addition to the large set of planning tools, integrated mathematical modeling approaches have been studied. The research of Balachandra and Chandru describes a linear programming formulation for an optimization problem [168]. The objective is to dynamically match supply in a resource constrained power system. As this model considers grid-connections, shortages can be compensated via imports. Alternatively, deficiencies could be overcome by storage systems. According to Brown et al. a pump-storage system allows for a larger penetration of variable RES and thus increases system security [169].

A rather practical approach for matching electricity supply and demand has been undertaken by Verma et al. [170], whereby it is aimed to contradict the unpredictability of electricity supply from variable RES by using smart meters and home automation systems. Via real-time pricing it is intended to stimulate or constrain user demand, and thus reduce the energy bill.

Besides the variety of studies and tools listed above, traditional optimization problems have to be considered. These include unit commitment (UC) and economic dispatch (ED). Both concepts are alike, with the major difference being that unit commitment also solves an additional decision variable for whether or not a unit is switched on and off.

UC is an optimization problem to identify a combination of generating units in the most cost-effective way. Several generation and transmission constraints need to be adhered to meet the forecasted load. Typically UC is performed over short time periods, typically a day or a week, whereby common generator parameters such as minimum run time, minimum down time, ramp rates, notification times, etc. are taken into account. However, the production levels are not defined. This only happens up to 5 minutes before the actual delivery in the so-called economic dispatch, which identifies "*the least-cost usage of the committed assets during a single period to meet the demand*" [171]. Several studies to analyze the integration of variable renewables have been undertaken by [172], [173], [174] or [175].

Lastly, to supply any consumer with electricity a transmission or at least distribution network is essential. When dealing with high shares of renewables, then expansions of the network infrastructure often become necessary [176].

2.7. Sustainability assessment and multi-criteria decision analysis

Sustainability is certainly one of the major characteristics for the realization of nearly any renewable energy project. Often, it is only economic sustainability that is being accounted for the success of a project, whereas a continuous trend of economic growth over time is expected. However, it is the planets sustainability with regards to global climate change that should be considered in any planning aspect. Thereby, maintenance of the environmental equilibrium at the global level must be maintained.

At the local level we used for quite some time the ecological footprint, which measures the bio-productive land and sea needed to supply the human's need for products and services. Most critical is the fact that the global average ecological footprint of a human is around 2.7 global hectares, but the global average bio-productivity is only around 2.1 hectares of land and water per capita [177].

In order to undertake comprehensive and robust sustainability assessments the criteria under evaluation need to be determined clearly, whereby *"criteria are the intermediate points to which the information provided by indicators can be integrated and where an interpretable assessment crystallizes"* [178]. Due to the often high number of criteria, multi-criteria decision analysis (MCDA) methods are applied to energy planning problems to support decision and policy makers. Hereafter, a brief overview of different MCDA methods along with applied criteria will be presented.

2.7.1. Sustainability assessment

Ness et al. [179] define *"The purpose of sustainability assessment is to provide decision-makers with an evaluation of global to local integrated nature–society systems in short and long-term perspectives in order to assist them to determine which actions should or should not be taken in an attempt to make society sustainable".*

A large variety of sustainable development criteria and sustainability assessment methodologies is presented in [180], [181]. Thereby, an overall of 41 criteria was identified and classified according to number of sub-criteria, scaling/normalization, weighting and aggregation.

According to the literature, various sustainable criteria have been applied to RES in sustainability assessments. The selection of effective criteria is crucial as they need to meet the characteristics of a problem and/or purpose. Usually each criterion is defined by several sub-criteria. Afgan and Carvalho use a set of four sustainability criteria (resource, environmental, economic and social) for the selection of renewable energy power plants [182]. The considered sub-criteria are efficiency (%), installation cost (USD/kW), electricity cost (c/kWh), CO_2 ($kgCO_2$/kWh) and area (km^2/kW).

Another approach which only considers techno-economic criteria for onshore wind, offshore wind, geothermal power, solar power, photovoltaic power and small hydropower was presented by Baysal et al. [183]. While the technical criterion is composed of construction period, technical lifetime, capacity factor and maximum availability, the economic criterion is represented through investment cost, fixed and variable operation and maintenance costs as well as progress ratio. A more comprehensive list of criteria and sub-criteria is presented by Wang et al. [184] (see Table 2-6).

Table 2-6: Selection criteria for sustainable energy planning

Criteria	Sub-criteria
Technical	Efficiency, exergy efficiency, primary energy ratio, safety, reliability, maturity, others
Economic	Investment cost, operation and maintenance cost, fuel cost, electric cost, net present value, payback period, service life, equivalent annual cost, others
Environmental	NO_x emission, CO_2 emission, CO emission, SO_2 emission, particles emission, non-methane volatile organic compounds, land use, noise, others
Social	Social acceptability, job creation, social benefits, others

For storage technologies the selection process is based on different criteria, mainly because of the services they need to cover. Barin et al. divide in qualitative and quantitative criteria to determine the storage energy technology in a power quality scenario [185]. Thereby, qualitative criteria focus on load management, technical maturity and power quality; with the respective sub-criteria being load leveling, load following, spinning reserve, backup or typical usage.

A sustainability index approach was undertaken by Raza et al. [186], whereas a weighted sum approach was used to quantify each criterion according to its importance. Criteria ranged from economic and environmental to risk, but also considered reliability, system life or energy density ratio. The evaluation reviewed lead acid and lithium batteries as well as fuel cells, whereas fuel cells come top in the selection process. Further selection procedures that considered similar selection criteria and sub-criteria as the above researches are presented in [187], [188], [189].

This section clearly demonstrated that there are many common criteria and sub-criteria for sustainable energy planning. Nevertheless, it is essential to select an appropriate set of criteria with strong sub-criteria based on the objective of the decision maker (DM). The whole assessment should be considered as integrated process rather than a solitaire one.

2.7.2. Multi-criteria decision analysis methods

MCDA can be an alternative to support decision and policy makers. Depending on the decision or policy maker different approaches can be considered to achieve an adequate decision. The selection process of an appropriate MCDA for renewable energy planning is discussed in [190]. According to Beccali et al. the objectives of MCDA are [191]:

- *"to aid decision-makers to be consistent with fixed 'general' objectives;*
- *to use representative data and transparent assessment procedures; and*
- *to help the accomplishment of decisional processes, focusing on increasing its efficiency."*

Very comprehensive reviews of MCDA were undertaken by [192], [193]. The analyzed methods include weighted sum/product method, analytical hierarchy process (AHP), preference ranking organization method for enrichment evaluation (PROMETHEE), elimination and choice translating reality (ELECTRE), technique for order preference by similarity to ideal solutions (TOPSIS), compromise programming (CP) and multi-attribute utility theory (MAUT) [194]. Additionally, Wang et al. [184] present fuzzy set methodology, grey relational method and others (Preference assessment by imprecise ratio statements (PARIS)) as MCDA methods for sustainable energy decision making.

An integrated approach considering MCDA along with Geographic Information System (GIS) models has been established in [195]. Indeed, combinations of GIS and MCDA are used to identify site locations for the installation of technologies; e.g. wind [196], solar [197] or tidal stream [198].

Extensive research in the permanent literature has been undertaken to assess the current state of the art of applied and conceptual research in the area of MCDA for renewable energy and storage systems (Appendix A – Table A-1 p. i ff.). Therefore, the purpose, criteria, sub-criteria and MCDA method for each research were analyzed. Plus, the data type of sub-criteria (quantitative, qualitative or mixed) and an evaluation if offshore and storage technologies were included in these cases were deliberated. Additionally, the applied system size and location as well as the considered technologies were summarized.

The review of MCDA for renewable energy and storage systems highlights:

- Most research is undertaken for technology selections and power system optimization;
- Offshore and storage technologies lack consideration;
- Combinations of offshore RES and storage technologies could not be identified;
- Criteria vary, but the most common one are: technical, environmental, economic and social
- The chosen sub-criteria vary strongly (the most common by criteria are; technical: efficiency, availability and lifetime; economic: investment cost and O&M cost; environmental: CO_2 emissions and land use; social: job creation, acceptability);
- The majority of studies use mixed data sets with an average of 8-10 (sub-)criteria; and
- AHP is the most frequently applied method in the analyzed researches.

When it comes to the applicability of reviewed studies (Appendix A – Table A-2 p. vi ff.), immediately the high focus on PV (>75%) and wind (>70%) becomes evident. Moreover, biomass, hydro and non-renewables are assessed in around 50% of the researches. Hydrogen and offshore technologies only play a marginal role. In terms of system size various studies focus on island energy systems, but with a limited number of technologies. Moreover, it is essential to highlight that none of the studies focused on all technologies. Out of 46 studies reviewed only twice offshore technologies were considered [199].

2.8. Renewable energy sources generation on islands

Globally, the implementation of RES on islands has received growing devotion in recent years. Many studies focus on supply alternatives based on PV and/or wind [130], [200], [201]. In several cases storage was also considered; mainly in the form of pumped hydro storage, hydrogen or fuel cells [133], [202], [203], [204]. It is important to notice that in most cases the ultimate goal was not to supply 100% of the energy (in this case electricity) needs with RES, rather than using the storage system to balance demand and supply. In terms of considering geothermal, biomass or hydro power as a supply alternative on islands, the research is still limited.

In contrary to the above studies, El Hierro [81], La Graciosa, Tenerife (all Spain), Aeroe, Samsoe [205] (both Denmark), Pellworm (Germany) or Gotland [206] (Sweden) are some cases that focus on electricity 100% RES based [203], [207], [208]. Plus, a stand-alone hybrid renewable energy/hydrogen power system to cover all energy needs has been studied for the island of Karpathos, Greece [155].

2.9. Gaps identified in literature review

The energy breakdown by sector, vector and services has demonstrated the value of shifting thermal and transportation needs to electricity generated from RES. Yet, studies are scarce. Measures for energy vector shifts are sought and need to be proposed. In a first attempt, understanding should be obtained of how and by how much the current energy needs can be electrically driven.

Within the concept of energy sufficiency there lies a great, yet untapped, potential to reduce the current energy consumption. While often sustainable development is instantly connected with energy efficiency and renewable energy, energy sufficiency guidelines can help redefining the energy needs to the essential ones. However, it is still not certain by how much the current consumption level can be reduced.

Another major gap represents energy planning with offshore technologies. Often offshore RES (apart from wind) are omitted from the beginning of most planning studies and researches. However, these technologies improve on a rapid scale and several countries are shifting their focus already to the sea. Strategies and conditions for the integration of offshore RES in the supply system still need to be developed.

While increasing levels of RES integration have been studied on several islands, it remains a major challenge to supply electricity on an isolated island entirely from RES and storage devices. Since variable RES are subject to a high degree of uncertainty, aspects of RES diversification and storage system integration have to be challenged more thoroughly. The analyzed optimization methods such as UC or ED present common practice for short-term system planning. However, these methods consider a very short period of time (usually only days or up to a week). More emphasis should be placed on assessing the changes that occur over longer periods, i.e. season or year, since this is particularly important for the determination of an adequate storage system size (in terms of energy – MWh) when planning for the integration of up to 100% RES. Besides, it is essential to take into account the daily variations and interactions of demand and supply. In previous works only selected days or worst-case scenarios are analyzed, which in fact, present limited results to support decision makers.

Since most sustainability assessments are predetermined in their criteria/indicator weights, the proposed methodology allows users to set their own priorities and preferences, thus giving them the opportunity to compare the results with a general case based on common practices.

3. Proposed methodological approach

In order to adhere to all research questions and to take on the gaps that were identified in the literature review a methodological framework is proposed. Initially, this chapter provides a brief overview of the overall framework and its procedures. Then, energy planning aspects on the demand side are analyzed thoroughly to build load profiles that reflect the future demand development. Lastly, the mathematical formulations for the time series algorithm are presented.

3.1. Overview of methodological framework

The proposed framework is clustered in four individual but subsequent work packages (WP) (Figure 3-1). Each WP requires the input of data and/or information. Models are established for each WP to analyze the inputs and provide outputs for the succeeding WPs, except for WP4 where the final results will be obtained.

WP1 reflects upon the demand development and incorporates energy planning and energy management strategies to build load profiles for various future scenarios taking into account increasing levels of final energy being based on electricity. These load profiles form the demand component for the time series algorithm of WP4. WP2 assesses the resource availability and site characteristics to identify locally suitable RETs that will undertake MCDA in WP3 for preliminary technology selection. Only the technologies selected in WP3 are then considered as possible supply components in the time series algorithm of WP4. In order to match demand and RES supply adequate backup in the form of storage will be defined. The procedures to build the load profiles for each scenario (WP1) as well as the mathematical formulation for the time series algorithm (WP4) are discussed within Chapter 3. The resource assessment (WP2) and technology selection (WP3) are then described in Chapter 4.

An initial idea of this concept was discussed at the International Conference on Energy and Environment Research 2014 and was published in [199]. Henceforth, a modified and adjusted version of the framework is presented.

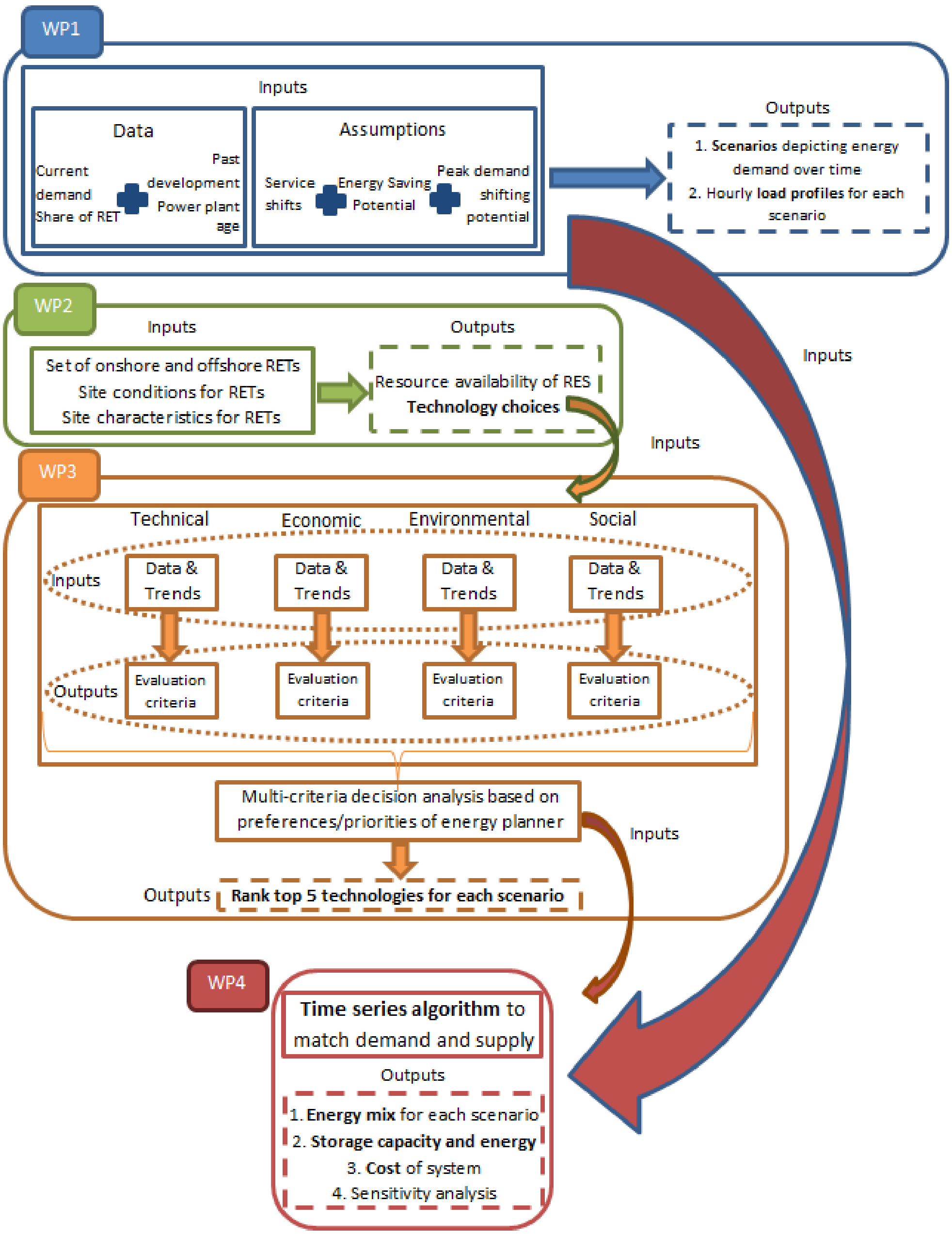


Figure 3-1: Illustration of conceptual work packages and subsequent procedures

WP1: Define demand and load profiles

The primary step is to define the current energy demand. Therefore, the peak capacity, annual demand and daily load profiles are sought. Despite having numerous external factors, various externalities that might influence the future energy demand such as the influence of tourism, policies, migration, large electric vehicle fleets, etc. are not considered. From an excessive possibility of scenarios 18 different ones are built. The 18 scenarios are the combinations of three alternatives (Janus[13], Aurora[14] and Antevorta[15] [209]) stating the amount of electricity to

[13] Janus is the god of beginnings and transitions, but also gates, doors, doorways, passages and endings in ancient Roman religion and myth. Janus is often depicted with two faces symbolizing his looks to the future and to the past.

be covered from RES along with three time frames (10 years, 20 years and 30 years) as well as a regular load (RL) shape and one that includes load shifting (LS). Despite a set of pre-defined rules, LS is also expected to be a result of large scale implementation of smart grid concepts and higher awareness of consumers to energy-related issues. The scenarios are chosen to reflect a great variety of planning aspects that are interesting for energy planners and decision makers. If adequate data and information according to the scenario building of Chapter 3.2.7 can be provided, the subsequent WPs are able to evaluate any scenario. The three alternatives for RES integration within this research are defined as follows:

- Janus intends to fulfill the future additional electricity demand (difference between current status and the expected demand of considered time horizon) and whatever demand results from the phase-out of fossil fuel power plants with RES.
- Aurora foresees replacing all fossil fuel power generation in the given time frame, whereas the time period is foreseen to be the driving factor for the selection of technologies. Over longer time periods it is expected to have higher shares of offshore RES since they are expected to become more cost-competitive.
- Within Antevorta all fossil fuel power generation plus all heating and transportation services that might become electric within the specific time horizon shall be covered from RES.

Table 3-1: Scenarios

		Time frame (years)		
		10	20	30
Alternative	Janus	Janus RL10	Janus RL20	Janus RL30
		Janus LS10	Janus LS20	Janus LS30
	Aurora	Aurora RL10	Aurora RL20	Aurora RL30
		Aurora LS10	Aurora LS20	Aurora LS30
	Antevorta	Antevorta RL10	Antevorta RL20	Antevorta RL30
		Antevorta LS10	Antevorta LS20	Antevorta LS30
		RL = Regular load shape		**LS = Load shifting**

For each of the 18 scenarios (Table 3-1) daily load profiles are required, depicting the hourly loads over the year. If precise measurements for every hour are scarce, the profiles for weekdays, Saturday and Sunday over the different months or seasons may be used. A

[14] Aurora is the goddess of dawn in Roman mythology. She renews herself every morning. As she flies across the sky, she announces the arrival of the sun.
[15] *Antevorta* represents the goddess of the future in ancient Roman religion.

minimum of 3 different load profiles across the seasons is desired to perform the time series algorithm in WP4.

The following assumptions are made for the construction of scenarios:

- In Janus RL10, Janus LS10, Janus RL20 and Janus LS20 it is expected to have enough fossil fuel backup available to integrate RES. If not, minor amounts of storage capacity might be required.
- Janus RL30 and Janus LS30 might already rely on larger storage capacities, but will most probably not be driven entirely by RES and storage.
- For all scenarios involving Aurora a replacement of all fossil fuel by RES can be done within the proposed time frames.
- Work on the generation side and/or network expansions are neglected in all scenarios.
- Within all scenarios comprising Janus or Aurora no energy vector shifts are performed.
- All scenarios including Aurora or Antevorta consider the use of solely RES and storage technologies in the initial sequences of the time series algorithm in WP4. In order to improve system reliability a minimum amount of fossil fuel backup may be considered. It is expected that due to the earlier ‘phase-out’ (replacement) of fossil fuel generators their lifetime (actual availability) will extend considerably compared to a typical generator that runs continuously. The final sequence of the algorithm will then perform some sensitivity analysis, including minor contributions from fossil fuels in the system.
- Scenarios comprising Antevorta consider different amounts of energy vector shifts to be undertaken over time. Thereby, the load will be increased proportionally in each hour of the day.
- Load shifting is performed for all scenarios whereas pre-defined shifts are applied (rules for shifts are established). The load shifts only vary in the quantity of end-uses to which the rules are applied in each scenario.

WP2: Resource assessment and local site characteristics

WP2 evaluates different RES according to the local resource availability and site characteristics. 42 different onshore and offshore renewable energy technologies are assessed within a technology pre-selection process. Several emerging concepts, especially for wave, tidal or hydrogen, can be added once more precise data is available. While the resource availability assesses the general suitability of each technology, different technology specific site characteristics shall further reduce the number of prospective technologies. The conditions to evaluate the resource availability and site characteristics are technology specific. They allow selecting RETs for each RES more precisely. For instance, within offshore wind there are floating and fixed devices, but due to the water depth around an island only floating devices might be suitable. Plus, within floating devices various considerations regarding the mooring dynamics, hydrodynamics, aerodynamics and so forth are applied. In contrast, for onshore technologies the conditions are more related to space limitation, shading or land accessibility.

In a similar manner as described for offshore wind, conditions for each renewable energy source are defined to detect the most appropriate RET(s). By means of a pre-selection algorithm it is intended to reduce the number of technologies that are considered for further evaluation and to identify the RETs that are suitable for the explicit site location. A comprehensive set of conditions has been defined for each technology option. Conditions can either be inclusive or exclusive. Inclusive means that a certain technology choice may be selected even if the condition cannot be met. Exclusive means that the technology choice will be excluded from further evaluation if the condition cannot be met.

WP3: Technology selection

A sustainability assessment will be undertaken for all pre-selected RETs over the three time horizons (10, 20 and 30 years). A set of criteria has been defined to evaluate the technologies under technical, economic, environmental and social aspects. Therefore, multi-criteria decision analysis (MCDA) in the form of multi-attribute value theory (MAUT) is applied. Learning curves over the time horizons are associated to each attribute value; e.g. efficiency improvements, cost reductions, local perception, etc. The swing weights method is then applied to associate weights to all criteria based on experiences gained from the literature review.

In a second approach these swing weights may be modified by decision makers, energy agencies or any other user of this concept to reflect their preferences and/or priorities more precisely. This will give applicants of this concept a higher flexibility in their decision making process and strategic planning, while also having a chance to compare their results with the benchmark provided in the initial evaluation.

Once all technologies are ranked accordingly, only the top 5 technologies (one RET per RES) of each time horizon are considered for further evaluation. Multiple technology choices of the same RES are not applicable. The diversity of technologies is desirable as the amount of storage can be reduced and system reliability can be improved.

WP4: Determination of energy mix

At this stage the RETs are pre-selected and their natural resource availability (which is converted to hourly capacity factors) is defined. The latter can be obtained from local weather stations. Additionally, the primarily conducted load profiles for each scenario are available (WP1).

Based on an hourly time series algorithm solutions for each scenario will be identified. In the first phase, the following parameters will be identified: capacities of selected RETs, storage capacity and energy size, spillage and total system cost. Initially, only one storage technology (pumped-storage) is considered.

In the second phase, minor contributions from thermal units (fast responding diesel engines) and a second storage system are foreseen. While the first storage system interacts with RES, the second storage, which is expected to be much smaller in capacity and energy size, only interacts with the thermal units. Some technical parameters such as system availability, reliability and loss of load are not addressed in this time series algorithm. However, commonly imposed constraints of unit commitments (e.g. demand balance, ramp rates, spinning reserve requirements and unit generation limits) are considered for the planning with thermal units.

Finally, modifications of the algorithm will be performed so that a better understanding of the changes of various parameters can be obtained. The parameters of greatest interest seem the amount of base load, the annual spillage and the effects of higher shares of fossil fuels on the overall system cost.

Following the overview of the methodological concept this chapter and the next (3 & 4) describe all four WPs in depth and apply them in context. Since substantial data is required to apply the whole concept in a real case and initially not all data could be obtained for the case of the Azores, real world data from a North-American and mainly European context was collected to illustrate, strengthen and modify the concept. For all WPs individual models are created by means of ‘Microsoft Excel’. The specific inputs, outputs, gathered datasets as well as assumptions are stated within each step of the concept.

3.2. Defining demand and load profiles

The base for all further evaluations is formed by the energy (from now only refers to electricity if not stated differently) demand development. Load profiles are used to reflect the hourly demand, including daily, weekly and even seasonal changes. Within WP1 essential development aspects are highlighted and 18 scenarios are built.

3.2.1. Characterizing current demand and load profile

While approximate estimates of the energy demand (concerning electricity, heat and transport fuels (TF)) for any location or area (region, city, country, etc.) can be determined, for instance from energy balances, statistics or measurements, varying approaches (including top-down, bottom-up or mixed) are applied. In the case of isolated systems the identification of energy flows is straightforward, since neither an import from a power network nor an overlapping or interference with neighboring systems occurs. Hence, the sum of all energy inputs must equal the output along with all conversion and transmission losses.

Part of the characterization of the current demand is to analyze energy flows, whereas so-called energy flowcharts can be applied (Appendix B – Energy flowchart p. vii). They break down the primary energy sources in energy vectors[16] and depict their flows into the different sectors (residential, commercial, industry and transport). Thereafter, further differentiation in useful energy can be undertaken for each sector.

The flowchart in Appendix B represents the EU-27 and demonstrates that electricity covers only around one third of all final energy needs. In many countries and regions similar shares can be found. Frequently, the majority of electricity is provided from fossil fuels. Hence, there is considerable potential to increase the share of electricity based on RES. Shifts from heat and transport fuels are encouraging. However, this does not imply that all energy needs have to be covered with RES based electricity. Alternatives for heating with RES may include solar thermal or geothermal devices. Also, there are several prospects of using biomass for either heat (e.g. combined heat and power) or as transport fuel (biofuels). It is not the focus of this research to analyze how these non-electric RES alternatives can contribute to replace fossil fuels.

Because energy demand is usually presented on a yearly basis (or at least over a longer period, e.g. month or season) and includes all energy sources for all energy services, the highly variable demand over shorter periods (e.g. minute, hour or day) is not reflected adequately.

[16] Energy vectors are divided into electricity, heat and transport fuel.

The critical point for any energy system is to meet demand at all times. While fast responding fossil fuel driven generators are capable to respond to demand increases or decreases rapidly, the increasing penetration of variable RES requires careful planning and backup. In this context and with an increasing integration of variable RES short-term planning is essential for frequency control, system stability or power control. All short-term planning aspects are not considered within this research.

As initially stated, island energy systems have substantial load changes over the year; in extreme cases even by a few fold. It is deemed reasonable for this research to hearken back to hourly loads to match consumer demand with RES based electricity supply. Typical cases of single day profiles are presented in Figure 3-2 and Figure 3-3. While the bars present the load of a specific day (in this example a Wednesday), the blue line states the average value for each hour of the year on that day. Additionally, the pink line illustrates the maximum values on each Wednesday and the green line the minimum values. A significant demand variation can be experienced within one year. The daily profiles are of great interest since they provide a rational for energy management strategies on the demand side. Especially for the later imposed load shifting, the daily profiles can help in establishing rules for the shifting of loads from peak to off-peak hours. Across the scenarios costs of the overall system are compared for a regular load (RL) profile with one that is subject to load shifting (LS) to emphasize the need for demand side management measures.

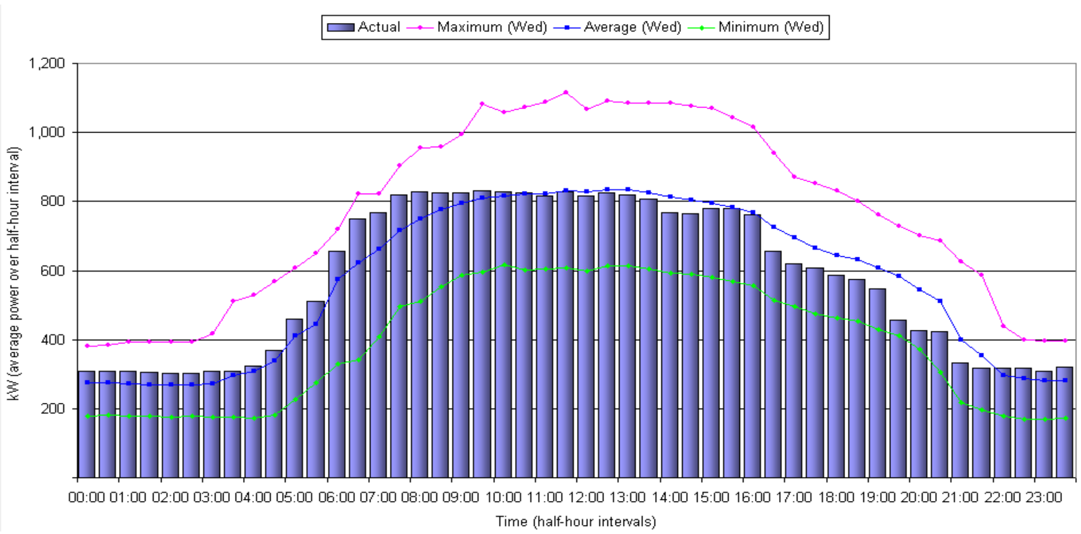


Figure 3-2: Single day profile [210]

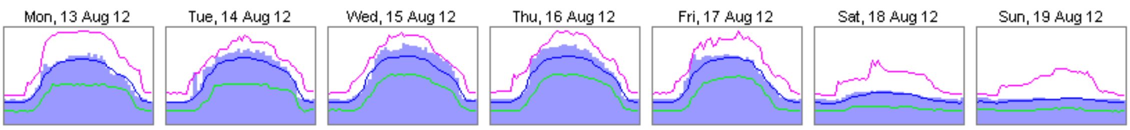


Figure 3-3: Daily load profile over the period of a week [210]

It is important to recognize the possibility of significant changes between weekdays and weekends which are mainly driven by industrial and commercial business activities. Since most islands do not have excessive industries or energy intensive users, the difference between the different weekdays is expected to be smaller [211]. However, significant peaks can be the result of a special occasion or high tourism activity on a specific holiday or due to an event/festival. Ultimately, for the data requirements of the time series algorithm, the load profiles shall determine the electricity requirements over the year. For each hour of the year, either with regular load (RL) or after load shifting (LS), a quantitative demand value shall be provided for the algorithm in WP4.

While electricity consumption can be measured very precisely and for each instant, the use of heat and transport fuels is more challenging to analyze.[17] The major difference consists of having energy when it is needed. Both, heat and transport fuels are storable and can be used whenever they are required. Electricity, on the other hand, should be used when generated, unless additional means of storage are available. Subsequently, alternatives of electricity storage have to be identified and incorporated in system planning.

For the incorporation of energy vector shifts from heat and transport fuels (TF) to electricity one major assumption was made for the load profiles: all heating and transportation needs follow the same pattern as electricity consumption. Hence, the load profile will not change in shape, but only in the amount of electricity needed in each hour.[18] Further elaborations about vector shifting are discussed in Chapter 3.2.4 (p. 42 ff.).

3.2.2. Analyzing past development

Data, information and statistics about the historical trend of energy demand are the main sources to extrapolate the future development. For long-term planning it is imperative to define how demand might change over the next decades. Thereby, it is not necessarily always an increasing trend that can be expected.

Over a decade several increases and decreases might occur from one year to another, but when analyzing the changes over a whole period (10, 20 or 30 years) one might associate an annual average increase or decrease. Major drivers for future development include tourism

[17] Often it is only the amount of heat and transport fuels that is recorded or registered by meters, but not the time at which the energy vector is used.

[18] Even though this assumption does not reflect the consumption behavior entirely, it represents an assumption about the time of use. As a matter of fact, transportation to work would occur around the morning peak, probably with a slight delay from the use of electric appliances at home. Similarly, the return from work occurs just around the afternoon peak. During this time further increases would occur due to the shift of heat to electricity. In fact, space heating or cooking would occur at around the same time when using electricity instead of the conventional means. Yet, further research on the effects of load shifting is required, since demand variations over time are critical for island power systems.

activities, limited spatial availability, expected emigration, etc. Since efficiency improvements are considered separately when conducting the load, it is another assumption to foresee persistent increases or decreases over the considered time periods (e.g. increase/decrease of 2% per year).

In addition to development trends it is essential to determine the age structure of all electricity generating units. This is of great importance, since the increasing penetration of RES requires adequate backup and fossil fuel power plants could still be used as emergency backup until the end of their lifetime to guarantee higher energy security of the overall system and postpone investments in colossal storage systems.

3.2.3. Energy saving measures

New appliances and technologies, both, on the demand and supply side[19], are changing the current energy system to become more efficient. As long as the theoretical optimum is not reached there is always space for (marginal) improvements.

This section analyses measures to reduce the overall energy demand. Despite the fact that various measures exist to reduce consumption, each measure has its constraints and limitations. De Oliveira Fernandes et al. [212] describe different technical energy saving measures and the respective key barriers for the building stock as well as transport and mobility. Further measures and their saving potential are documented in Table 3-2.

Depending on the current level it is stated by de Almeida et al. that up to 48% of electricity can be saved within the residential sector due to improved technologies and consumer behavior [213].[20] It is not one measure in particular that bears such high saving potential, rather than the combination of a large variety of measures to reduce demand.

Besides presenting a variety of measures for the residential, commercial and transport sector, Table 3-2 tries to exemplify how many percent of appliances and services can achieve such savings over the next 30 years – relative to the current level. The saving potential indicates the involved energy vector and by how much the final energy requirements can be reduced. All measures without reference are estimations and therefore require further research and/or validation (also see footnotes within Table 3-2).

[19] This research will only focus on saving measures on the demand side. Efficiency improvements on the supply side are not considered. Savings in the industry sector are not considered since the share of the industrial sector on small island systems is usually insignificant or the type of industry is very site specific.
[20] This does not include space and water heating.

Table 3-2: Measures to reduce annual energy demand

Sector	Measure	Saving Potential [1]	% applied by end-user in 10 y	20 y	30 y	Ref.
Residential	Improve construction from existing average to typical new or from typical new to passive house	H/E: 50-65% space heating	30%	50%	85%	[214]
	Saving fixtures; efficient, insulated & tankless heaters	H/E: 90% water heating	30%	55%	95%	[215]
	Efficiency improvement of appliances	E: 30% electric appliances	50%	70%	100%	[216]
	Use efficient lighting technologies & daylight	E: 75% lighting	75%	90%	100%	[215]
	Efficient appliances for cooling	E: 90% cooling	20%	40%	75%	[215]
	Improve technology from present to current best	E: 25% cooking	30%	55%	90%	[213]
Commercial	Study: considers building envelope (U-values for walls & glazing) and amount of glazing; assumptions are based on improvement from average to minimum	H/E: 27% space heating	10%	20%	40%	[217]
		E: 6,5% cooling	10%	20%	40%	
		H/E: 2% water heating	10%	20%	40%	
	Efficiency improvement of appliances	E: 30% electric appliances	50%	70%	100%	[216]
	Manual dimming and switch-off occupancy sensors	E: 27-60% lighting	75%	90%	100%	[217]
	Improved technology and usage	H/E: 31% cooking	50%	70%	100%	[218]
Transport	Car sharing [2]	E/TF: 49% cars	5%	7%	10%	[219]
	Driving style	E/TF: 10-25% cars/trucks/buses	5%	10%	20%	
	Use public transport [3]	E/TF: buses, public transport 30-60%	5%	10%	20%	
	Work from home or use non-fuel transportation; e.g. cycling [4]	E/TF: 100% cars; public transport	2%	3%	5%	
	Drive train, body improvements and hybridization technologies	TF: 50% cars	30%	40%	60%	[220]
		TF: 50% trucks/light vehicles				
		TF: 50% buses/motorcycles				
			Saving potential within time horizon			
	Energy intensity improvement potential (values consider all transportation means)	TF: air	30-40%		50-65%	[221]
		E/TF: rail	15-17%		30-35%	
		TF: water	40%		50-75%	
	Technical potential (on average 2,8%) for energy efficiency improvement – passenger transport considers specific energy use in MJ per passenger and freight transport considers MJ per ton-km	E/TF: cars	3.2% per year			[222]
		E/TF: trucks/light vehicles	2.3-3.2% per year			
		E/TF: buses/motorcycles	0.8-2.3% per year			
		E/TF: air	2.6% per year			
		E/TF: rail	1.0-1.7% per year			
		E/TF: water	1.4% per year			

[1] Final energy saving potential by end-use service & energy carrier: E = electricity; H = heat; TF = transport fuels 10, 20 and 30 years indicate the percentage of improvement within residential and commercial buildings as well as transport

[2] Car sharing assumes that consumption can be almost cut half, since at least 2 passengers use the same vehicle. A slightly higher consumption occurs for passenger 1 since the way to passenger 2 needs to be accounted for. If several passengers share the same car, the savings might be even greater.

[3] The use of public transportation bears a broad band for saving potential depending on the type of transport vehicles, consumption compared to a passenger car, the amount of passengers using the vehicle, the distance to reach from A to B, etc. Generally, if more passengers use public transport, the saving can be proportionally greater.

[4] Working from home completely avoids the use of transport to work and therefore the savings are 100%.

The saving potentials that will be applied to conduct the load profiles are listed in Table 3-3. Therefore, an analysis is undertaken that focuses on the share of each end-use service within the residential, commercial and transportation sector. Based on those services along with each sectors share the saving potentials over 10, 20 and 30 years are identified. For the shares of end-use services it may be referred to the energy breakdown presented in Appendix B – Energy flowchart. If the useful energy demand for a specific case study can be broken down in its end-uses, then the saving potentials defined in Table 3-2 may be applied directly to each end-use.

For the residential, domestic and transportation sector the saving potentials are applied to each end-use service with the percentage that is expected to be applicable by that end-use within the time period. Then, the total savings within each sector can be defined. If multiple saving measures are listed for the same end-use, further modifications of the total savings are required. In such a case, like for cars, an assumption for the expected savings from all measures as well as an expected percentage for the application of all measures had to be made. For both, the percentage to be applied, but also the saving potential, increasing saving potentials are considered. The procedures are repeated for trucks and light vehicles as well as for buses and motorcycles. For rails the major focus was placed on the energy intensity improvement that can be achieved over time. Assumptions were then made for the percentage of rails that will apply such improvements.

Often saving measures are subject to support mechanisms, mainly financial support (such as incentives) or educational and policy mechanisms in order to raise awareness and also achieve high savings in the energy system. Within a pre-defined area, such as a city or island, the possibilities of achieving high levels of change are believed to be higher than in areas where the population lives more dispersed. Nevertheless, various structural issues in energy policies towards the new energy paradigm have to be kept in mind [223].

Table 3-3: Expected electricity saving potential by sector and over time

Sector	Demand (toe)	End-use service	Demand (toe)	Share (%)	Saving potential in 10 years				Saving potential in 20 years				Saving potential in 30 years			
					saving potential	% applied by end-user	actual savings (toe)	total savings (toe)	saving potential	% applied by end-user	actual savings (toe)	total savings (toe)	saving potential	% applied by end-user	actual savings (toe)	total savings (toe)
Residential	72.5	space heating	13.8	19%	50%	30%	2.07		50%	50%	3.45		50%	85%	5.87	
		water heating	8	11%	90%	30%	2.16	18.61	90%	55%	3.96	26.86	90%	95%	6.84	39.02
		electric appliances	37.7	52%	50%	50%	9.43		50%	70%	13.20		50%	100%	18.85	
		lighting	8	11%	75%	75%	4.50		75%	90%	5.40		75%	100%	6.00	
		air-conditioning	0.7	1%	90%	20%	0.13	26%	90%	40%	0.25	37%	90%	75%	0.47	54%
		cooking	4.4	6%	25%	30%	0.33		25%	55%	0.61		25%	90%	0.99	
Commercial	71.7	space heating	8.8	12%	27%	10%	0.24		27%	20%	0.48		27%	40%	0.95	
		water heating	4.4	6%	2%	10%	0.01	14.93	2%	20%	0.02	17.48	2%	40%	0.04	23.63
		electric appliances	25.9	36%	30%	50%	3.89		30%	50%	3.89		30%	100%	7.77	
		lighting	22.7	32%	60%	75%	10.22		60%	90%	12.26		60%	100%	13.62	
		air-conditioning	6.5	9%	7%	10%	0.04	21%	7%	20%	0.08	24%	7%	40%	0.17	33%
		cooking	3.5	5%	31%	50%	0.54		31%	70%	0.76		31%	100%	1.09	
Transportation	3.6	cars	0.3	8%	40%	40%	0.05		50%	60%	0.09		60%	80%	0.14	
		trucks and light vehicles	0.1	3%	40%	40%	0.02	0.36	50%	50%	0.03	0.66	60%	75%	0.05	1.09
		air	0	0%	-	-	-		-	-	-		-	-	-	
		rail	2.5	69%	15%	60%	0.22		25%	70%	0.43		35%	85%	0.74	
		water	0	0%	-	-	-	10%	-	-	-	18%	-	-	-	30%
		bus and motorcycles	0.7	20%	35%	30%	0.07		40%	40%	0.11		45%	50%	0.16	
Industry: no saving potentials are assessed																

3.2.4. Vector shifting potential

Renewable energies are an abundant and inexhaustible energy source. Therefore they can be considered 100% efficient at the final energy level (Chapter 2.1 – p. 9 ff.). High conversion losses that usually occur in electricity generation from fossil fuels can be eliminated. At the same time, a vector shift towards electricity confines the losses of heat and transport fuels at the end-user level, where electricity is the most efficient energy vector.

The reasoning to aim for higher shares of electricity is the adaptability of residential and commercial sector services to use electricity. Also, there is reasonable potential for changes in the transport sector. Since electric vehicles present an alternative form of storage system, their integration becomes even more attractive for (isolated) energy systems that seek for fossil fuel independence. By using smart energy networks and devices the electric vehicle load could follow RES generation. Besides, the often limited travel range of electric vehicles will only be of minor importance on islands, where long distance travel is rather unusual, except for some public transportation. Industry services have a rather low share and are not as flexible as other services. Subsequently, they will be omitted in the shifting considerations.

For the energy breakdown of useful energy services in the residential sector it may be referred to Figure B-2 in Appendix B – Energy flowchart, which continues the analysis of the EU-27. Thereby, it becomes clear that space heating is responsible for the largest share, followed by electric appliances and water heating. Considering the below example the following vector shifts for the residential and commercial sector are assumed over time:[21]

- 25%, 50% and 80% of all heat for space heating can be electric in 10, 20 and 30 years
- 25%, 50% and 80% of all heat for water heating can be electric in 10, 20 and 30 years
- 50%, 75% and 100% of all heat for cooking can be electric in 10, 20 and 30 years
- All electric appliances, lighting and air conditioning are based on electricity only

The resistance to shift to an electricity-driven system increases noticeably within the transport sector. Nevertheless, the transport sector is already assigned towards new concepts; mainly the substitution of fossil fuel vehicles with other alternatives such as electricity, hydrogen, biofuels or combinations of the aforementioned. Based on the nature of technologies within the industry sector it is unlikely to substitute process heat or other heat intensive services with electricity-driven technologies in the near future.

[21] To further decrease fossil fuel dependency it would be ideal to cover the remaining percentages of space and water heating with heat generating RES. Such solutions are not discussed in this research.

Within the transport sector (Figure B-3 in Appendix B – Energy flowchart) the shifting potential is more challenging to foresee, especially as it is very difficult to cover all transport needs with solely electricity; yet not to mention in the foreseeable future. For this study the following assumptions are made:

- 5%, 10% and 20% of all TF in cars, trucks and light vehicles will be electric in 10, 20 and 30 years respectively
- All air transport remains entirely fossil fuel based over time
- 50%, 70% and 100% of TF in the rail transport will be electric in 10, 20 and 30 years
- All water transport remains entirely fossil fuel based
- 20%, 30% and 50% of all TF in buses/motorcycles will be electric in 10, 20 and 30 years

A summary of the expected vector shifts is presented in Table 3-4. Firstly, all non-electric end-uses have been identified for each sector (If precise information about the analyzed case study is available, the data with the specific shares of end-uses may be applied – in the specific case of Table 3-4 the breakdown of end-uses within the EU-27 was applied.). The saving potentials as defined above are then associated to each end-use so that the total shifting potential for each sector can be calculated.

Besides the shifting potential itself, energy savings due to the higher efficiency levels of electricity at the end-user level are analyzed. The energy efficiencies of various useful energy services are compared in Table 3-5 [224], [225], [226].

Regardless of the energy conversion from primary to final energy, the below depicted final energy savings can be achieved. Indeed, 30% of final energy can be saved in the residential and commercial sector for space heating if all heating appliances were shifted to electric ones.

Table 3-4: Expected energy vector shifts by sector and over time

Sector	Total final demand other than electricity (Mtoe)	End-use service	Final demand by service other than electricity (Mtoe)	Share (%)	Shifting potential in 10 years			Shifting potential in 20 years			Shifting potential in 30 years		
					Shifting potential	Actual shifting (Mtoe)	Total shifting in (Mtoe) and (%)	Shifting potential	Actual shifting (Mtoe)	Total shifting in (Mtoe) and (%)	Shifting potential	Actual shifting (Mtoe)	Total shifting in (Mtoe) and (%)
Residential	233.4	Space heating	194.2	83%	25%	48.55	59.68	50%	97.10	117.38	80%	155.36	186.22
		Water heating	28.7	12%	25%	7.18		50%	14.35		80%	22.96	
		Electric appliances	0	0%	0%	0.00		0%	0.00		0%	0.00	
		Lighting	0	0%	0%	0.00	26%	0%	0.00	50%	0%	0.00	80%
		Air-conditioning	0	0%	0%	0.00		0%	0.00		0%	0.00	
		Cooking	7.9	3%	50%	3.95		75%	5.93		100%	7.90	
Commercial	90.1	Space heating	75.3	84%	25%	18.83	24.18	50%	37.65	46.95	80%	60.24	74.00
		Water heating	10.2	11%	25%	2.55		50%	5.10		80%	8.16	
		Electric appliances	0	0%	0%	0.00		0%	0.00		0%	0.00	
		Lighting	0	0%	0%	0.00	27%	0%	0.00	52%	0%	0.00	82%
		Air-conditioning	0	0%	0%	0.00		0%	0.00		0%	0.00	
		Cooking	5.6	6%	50%	2.80		75%	4.20		100%	5.60	
Transportation	359.6	Cars	175.1	49%	5%	8.76	19.42	10%	17.51	36.00	20%	35.02	68.69
		Trucks and light vehicles	109.6	30%	5%	5.48		10%	10.96		20%	21.92	
		Air	51.2	14%	0%	0.00		0%	0.00		0%	0.00	
		Rail	4.8	1%	50%	2.40	5%	70%	3.36	10%	100%	4.80	19%
		Water	7.3	2%	0%	0.00		0%	0.00		0%	0.00	
		Bus and motorcycles	13.9	4%	20%	2.78		30%	4.17		50%	6.95	

Industry: no shifting potentials have been assessed. Hence, any energy shifting possibilities within the industry sectors share are neglected.
Mtoe = million ton of oil equivalent

Table 3-5: Final energy savings through energy carrier shifting

Service sector [1]	Useful energy service	Energy carrier	Appliance	Efficiency	Final energy savings
Residential/ Commercial	Space heating	Heat [4] Electricity	Fossil fuel heater Electric heater	70% 100%	30%
	Water heating	Heat Electricity	Gas water heater Electric heater	62% 100%	38%
	Cooking	Heat Electricity	Gas burner Electric ranges	55% 65%	10%
Transport [2,3]	Cars	Transport fuel Electricity	Automobile engine Small electric motor	25% 62%	37%
	Trucks and light vehicles	Transport fuel Electricity	Automobile engine Small electric motor	25% 62%	37%
	Rail	Transport fuel Electricity	Steam locomotive Large electric motor	10% 93%	83%
	Buses and motorcycles	Transport fuel Electricity	Automobile engine Small electric motor	25% 62%	37%

[1] Industry shifts will not be further considered. If there might be any shifting in the future, than electricity would replace the same amount that is currently covered by heat; so the final energy saving would be accounted with 0.
[2] Water and air transport were not further evaluated, as their shifting potential towards electricity is very low.
[3] For the comparison of transport vehicle efficiencies “fully diesel powered” and “fully electrical powered” are used.
[4] Considers an assumed average (70%) of a home gas furnace (85%), home oil furnace (65%) and a home coal furnace (55%); 70% were chosen as the share of gas heating systems is the most applied one.

3.2.5. Demand side management strategies

Power (electricity) control systems are used to manage electrical appliances according to the supply curve. Since control systems are very complex and the new energy paradigm encourages the interaction of demand and supply [9], the development of smart grids has received growing interest in recent years.

Modifications on the demand side are usually defined by six common management strategies (Figure 3-4). Following the discussions in Chapter 2.2.4 (p. 15), load shifting will be taken into consideration to reduce the peaks and to smooth the load. In the scenario building two types of load profiles will be analyzed, one that reflects upon a regular load (RL) without any modification and one that considers load shifting (LS) through a defined set of rules. By means of load shifting it is expected to flatten the load so that a higher base load capacity can be installed in the system and less peak capacity is required. Further studies might also take into account a flexible load shape, which is interesting for variable RES since it allows for a higher share of variable RES without additional backup, both, in terms of capacity and energy.

Changes in the time of use can mainly be achieved with electric vehicles (EV) [227], [228], [229] and wet appliances in households [230], [231]. A study by D’hulst et al. [232] indicates that the flexibility window per wet appliance is on average 8 hours. Hence smart appliances that are usually operated during the afternoon peak can be run at night. Recent studies also analyze the potential for pre-cooling/heating [233], [234], [235] as well as pre-heating of water [236].

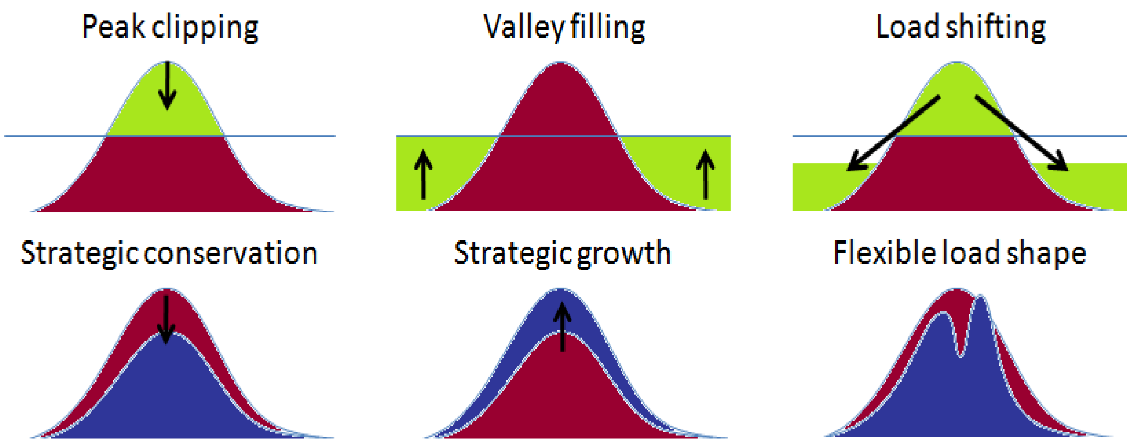


Figure 3-4: Types of demand side management strategies [48]

For all scenarios comprising LS a stringent approach for load shifts is chosen. Therefore, a set of rules is defined (Table 3-6) to smoothen the load. The same shifting procedures are applied across the different scenario alternatives and time horizons.

Table 3-6: Load shifting considerations to conduct load profiles for scenarios comprising LS

Sector	End-use for load shift	Load shifting considerations
Residential	Wet appliances	Explanation/assumptions: Wet appliances in households bear considerable potential for load shifting. Thereby, an 8 hour time shift is considered according to [232]. Rule: 80% of wet appliances will be shifted from the period 12pm-8pm to 8pm-4am. The usage of wet appliances between 4am and 12pm is not considered in the load shifting.
Residential and commercial	Space/water heating and cooling	Explanation/assumptions: Both, space and water can be pre-heated by a limited time period (for instance 2 hours). Similarly, pre-cooling can be performed. This provides an opportunity for load shifts from the morning hours to the off-peak hours earlier in the day. A minor load shift of space and water heating as well as space cooling is proposed. Rule: 5% of space and water heating as well as 10% of space cooling occurring during peak hours (8am-8pm) will be shifted two hours prior to its current actual usage, so that the overall peak can be smoothened and the morning off-peak (6am-8am) can already cover some demand.
Transport	Electric vehicles	Explanation/assumptions: Electricity consumption in the transport sector of islands is entirely associated to vehicles. It is assumed that on small islands there is no consumption by rails. Due to the limited size of islands the driving ranges are limited. The daily mileage range of EVs is unlikely to be exceeded and the EV battery only needs to be charged ones per day – during the night. Rule: 80% of all electricity consumption can be shifting to off-peak hours. 80% of all road transportation using electricity will be moved from 8am-8pm to 12am-6am. For representative purposes the hours 8am to 10am will be shifted to 12am of the following day. Each two hour interval will be added to one hour during the night off-peak. Consumption occurring between 8pm and 12am and from 6am to 8am will remain unchanged.
Notes: All other end-uses across the three analyzed sectors remain unchanged in the shifting considerations. Obviously, the proposed shifting potential (quantity) but also proposed time periods for shifts require further validation. The herein proposed load shifting measures seem reasonable within the island context. All aspects of adaptive behavior, which mainly concerns space heating/cooling, are not considered. Which such changes the overall consumption, and hence the peak demand, can be also reduced.		

In addition to the rules listed above a breakdown of end-uses for the residential and commercial sector is required, whereas the amount of wet appliances is of particular interest. If no precise breakdown of end-uses can be found for the application of load shifting, then the residential and commercial sector electricity breakdown of the EU-27 may be applied as benchmark (Figure 3-5)[22] (see also remarks of footnote 16– p. 35). Thereby, wet appliances in the residential sector are represented through dishwashers as well as washing and drying with a total share of 10.2%.

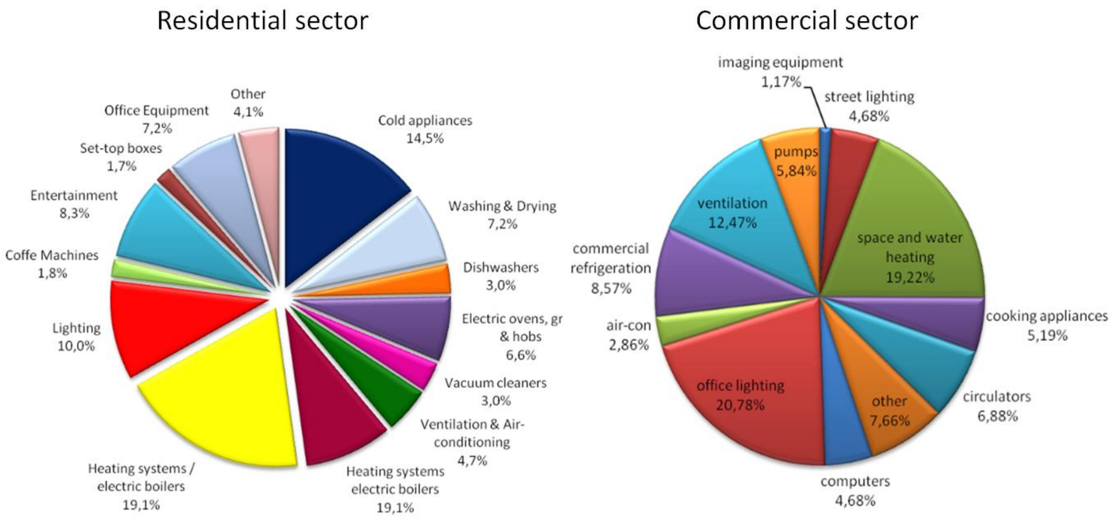


Figure 3-5: Residential and commercial sector electricity consumption breakdown in the EU-27, 2009 [237]

With the shares presented in Figure 3-5 and the rules implemented in Table 3-6 the load profiles for each scenario comprising LS are built. Load shifts for the different end-uses are applied only once the final demand is identified. The major influence of load shifts is associated to wet appliances and EVs. The potential to smoothen the load via heating and cooling shifts is restricted. Instead these shifts, associated with adaptive behavior, are suggested for further consideration in the conductions of a flexible load shape; where heating and cooling can try to follow RES generation.

3.2.6. Combining saving and shifting measures to build load profiles

Henceforth, all above presented aspects are combined to conduct the two load profile types (regular load and load shifting) that will be applied for the scenario building in Chapter 3.2.7. The sequence includes 4 steps that are identical for both load profile types. For the profile with load shifting an additional 5th step is added.

[22] An error occurs in the illustration of the European Commission Joint Research Centre - Institute for Energy and Transport for the electricity consumption of water heating. In Figure 3-5 the category of heating systems/electric boilers is listed twice. The smaller of the two sections is water heating and has a percentage of 8.8%.

Based on a regular load profile the common procedures of the sequence are explained (Figure 3-6). The sequence starts with the current demand (step 1), whereas a single day demand profile is used to demonstrate the case. The peak of that day is considered as benchmark and therefore is marked as 100%. Future alterations in consumption are illustrated in step 2. This example considers an increase in demand. Any efficiency and reduction gains are neglected in step 2. For a time period of 10 years a total increase of almost 34% is assumed (3% per year), making the initial benchmark to rise from 100% to 134%. The increased demand is added proportionally over time to each hour of the day.

In step 3 the shifting potential from heat and transport fuel to electricity is added to build a modified (further increased) load curve. This step will only be performed for scenarios comprising Antevorta. The increase occurs in each hour. Depending on the share of each hour on the overall demand, the increase through vector shifting is added proportionally. The shifting potential in this example is assumed with approximately 15%.

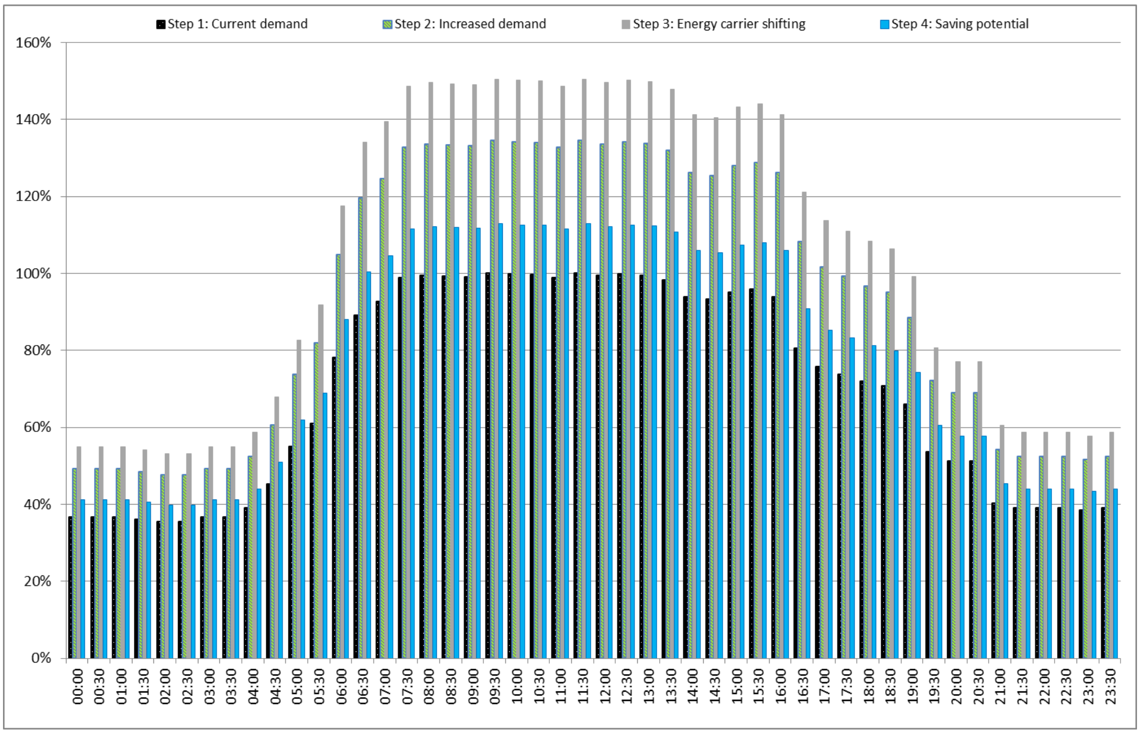


Figure 3-6: Stepwise procedures for regular load (RL) profile

The fourth step considers energy saving measures, efficiency plans and policies to reduce demand. Based on the share of each useful service the reduction potential is applied (step 4). In consequence, the shares are reduced on a proportional basis.[23] This procedure is

[23] On a proportional basis means that if demand in a certain hour is 100 MW and in another 60 MW, a saving potential of 30% would result in 70 MW and 42 MW respectively.

undertaken for each service and each measure. In the presented case an overall reduction potential of 30% is applied.

For all scenarios comprising LS step 5 involves shifting the time of use of certain defined end-uses. By applying the deliberations suggested in Chapter 3.2.5 the load profile in Figure 3-7 can be obtained. In general, a slightly lower peak demand along with a slightly higher base load band can be achieved (see circled areas). With an increasing contribution from EVs and further flexible end-uses the load profile could be further flattened.

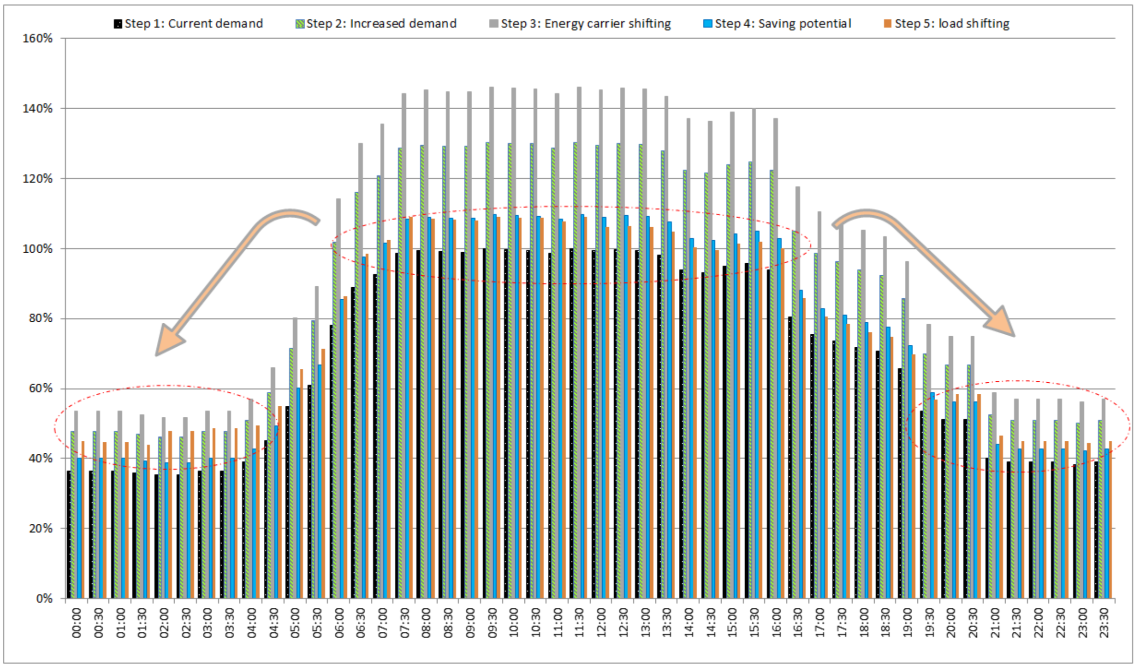


Figure 3-7: Stepwise procedures for load shifting (LS) profile

Table 3-7 gives a brief overview of all inputs, assumptions and datasets that are required to build the scenarios along with its load profiles. Inputs must be given from the user of the model. Assumptions can be made by either the user of this model or the currently given assumptions (benchmarks) can be applied. The outputs define all key elements for each scenario. After completing WP2 and WP3, solutions for each scenario will be analyzed in the time series algorithm of WP4.

Table 3-7: Summary of inputs, assumptions, datasets and outputs for WP1

Inputs	- Current primary energy consumption - Primary energy breakdown by source - Type of power generation units in use - Capacity of power generation units in use - Age of each power generating unit
Assumptions	- Breakdown of primary energy sources by vector - Primary energy usage by sector - Energy conversion rates from primary to final energy - Final energy usage by end-user appliance - Energy conversion from final to useful energy - Efficiency of end-user appliances - Vector shifts from heat or transport fuels to power follow the same "time-of-use" pattern as power consumption - Annual power demand increase/decrease - Identify potential for load shifts of end-uses; mainly wet appliances and transportation
Data sets	- Hourly load profiles over the period of 1 year - Energy saving measures for each end-use service by sector - Expected level of saving potential applied by end-users over each time horizon - Vector shifting potential by end-use, sector and over time - Load shifting potential and modified hours of usage
Outputs	- Regular load profiles for all scenarios comprising RL - Load shifting profiles for all scenarios comprising LS - Amount of power to be supplied from RES in each scenario - Expected phase-out of fossil fuel power plants

3.2.7. Building scenarios

Following the initial elaborations of WP1 the final section deals will the creation of 18 scenarios that reflect the prospective future energy requirements. Hourly load profiles are built as an input for application to the time series algorithm in WP4. While Janus intends to fulfill the future (additional) electricity demand and whatever results from the phase-out of fossil fuel power plants, Aurora foresees a complete replacement of fossil fuels over a given time horizon. Lastly, it is Antevorta that shall cover all fossil fuel generation as well as all energy services that can become electric within the time horizon with RES. Regular (unmodified) load profiles (RL) and profiles with load shifting (LS) are built and shall be compared in the time series algorithm of WP4. Current contributions from already installed RES also need to be identified.

3.2.7.1. Janus

Each scenario starts with an input/output sheet. Based on the example of Janus RL10/Janus LS10 [24] (Table 3-8) the required data and assumptions to establish the load profile for the different scenarios are presented and discussed.

[24] Scenarios alternatives of the same time horizon share the same input/output sheet for RL and LS, e.g. Janus 10 is applied to conduct Janus RL10 and Janus LS10. Hence, there are a total of 9 input/output sheets for 18 load profiles.

All fields that are marked in light blue require the input of data. The assessment begins with introducing a start year for the analysis along with the current total primary energy consumption either in TJ or GWh[25].

The next step (number 1) is to insert data regarding the power units; namely the type of unit, the number of units, the installed capacity (as a total of all units installed of the same type and the same construction year; i.e. 3 units with a total installed capacity of 3,000 kW indicate that each unit is 1,000 kW), either the approximate full load hours or the annual generation, the typical maximum full load hours that could be obtained from each power unit or set of units, and the year the units were built. Based on these inputs the total installed capacity as well as the annual generation can be obtained.

The two key figures (dark blue) are then transferred to the general data and assumptions section (number 2), where the share of electricity on primary energy demand is assessed. Besides, an indication about the current capacity of RES is given. The lower part of general data and assumptions requires the annual energy demand increase/decrease and annual power demand increase/decrease in percent per year. (For longer time horizons the percentage may be constant for the whole time horizon or varying across each 10 year period).

In the next input section (number 4)[26] the breakdown of electricity consumption by sector is required. This can be done either by percentage or sectorial annual consumption per year (the introduction of one value leads to the other one via conversion). In case no information about the breakdown by sector can be obtained, a pre-defined breakdown based on the literature review can be applied [53], [54]. Following the current breakdown a prediction of future shares (in this case in 10 years' time) is required. The shares of each sector will not change the shape of the load profile, but will cause varying increases or decreases of the profiles over time.

After all inputs are inserted, the outputs (right column of table) will be created automatically. Some important output values are presented in light green color. This includes the total primary energy and the electricity generation after 10 years. The latter is based on the annual increase or decrease of power demand. Besides, the electricity unit type and the year of construction will determine if a unit will phase-out within the scenario (red color). If so, then this part of the electricity generation shall be covered from RES. All fossil fuel units that are still in range continue operation and can be used as backup systems.

[25] The introduction of one value leads to the other one via conversion: 3.6 TJ equal 1 GWh

[26] Number 3 is reserved for the shifting potential which will be explained in the scenarios comprising Antevorta.

Based on the breakdown of final energy consumption by sector, the saving potentials for each sector (see Chapter 3.2.3. p. 38 ff.) are incorporated to identify the electricity demand after savings (dark green color).

Table 3-8: Data and assumption for load profiles of Janus RL10 and Janus LS10

Input data for the creation of scenarios			Output Janus RL/LS10
General data and assumptions			
Start year	-	2014	2024
Total primary energy	TJ/y	453,20	465,2
	GWh/y	125,89	129,21

1	Power unit type	Number of units	Installed capacity (MW)	Approx. full load hours (h/y) *	Capacity factor	Max full load hours (h/y) **	Annual generation (GWh/y) *	Built in	
	Thermal units - diesel	1	0,50	2.000	23%	3.500	1,00	1981	phase-out
		3	3,00	2.850	33%	3.500	8,55	1999	in range
		4	2,20	2.468	28%	3.500	5,43	1987	in range
		2	1,40	1.900	22%	3.500	2,66	2007	in range
	Wind	3	0,90	2.500	29%	2.500	2,25	1996	in range
	Total		8,00				19,89		

2					
	Power consumption		GWh/y	19,89	22,87
	Share of power on total primary energy demand		%	16%	18%
	Total installed capacity		MW	8,00	
	Available installed RET capacity for power generation		MW	0,90	
	Available installed fossil fuel capacity for power generation		MW	6,60	
	Annual energy demand	increase	%/y	1,0	
		decrease	%/y	-	
	Annual power demand	increase	%/y	1,5	
		decrease	%/y	-	

4		current		in 10 years		Saving potential by sector
	Breakdown final power consumption by sector	GWh/y *	% *	GWh/y *	% *	
	Residential		47,3%		50,3%	26%
	Commercial		38,1%		34,6%	21%
	Industry		14,1%		13,9%	0%
	Transportation		0,5%		1,2%	9%
	Power required after applying saving potential			GWh/y		18,20

5			
	Total power generation to be covered from RET	GWh/y	6,23
	Power generation required from new RET in 10 years	GWh/y	3,98
	Fossil fuel based in 10 years	GWh/y	11,96
	Maximum power available from fossil fuel units	GWh/y	25,35
	Peak power demand over the year	MW	3,10
	Available peak power: fossil fuel capacity + baseload RET * capacity factor	MW	6,60

* Requires the information of either approx. full load hours or annual generation or percentage or annual demand

** shall determine the upper bound of full load hours under which the fossil fuel units can be operated

The final section (number 5) of each table lists the key output figures and determines the expected generation from different electricity sources (RES or fossil). If RES are already installed, their contribution will be listed. Additionally, the maximum electricity available from fossil fuel units is given, whereby the upper bound of full load hours from the general data and assumptions section is applied.

The amount of electricity required from storage systems will be defined more precisely within the time series algorithm in WP4, since it highly depends on the RES to be deployed as well as their local resource availability.[27]

In a similar manner as Janus RL10/Janus LS10 the load profiles for all remaining Janus scenarios are built. The major difference lies in the increased penetration of RES over time as well as the modified (increased or decreased) load profiles that are obtained once all saving and shifting measures are implemented. Over time more and more fossil fuel units will phase-out and higher saving potentials can be achieved. While Janus RL20/Janus LS20 might not require a storage system yet, since adequate fossil fuel generation is available, in Janus RL30/Janus LS30 the introduction of a storage system is expected due to the increased phase-out of fossil fuel units. Over time the load profiles for Janus are similar in shape, since there is no vector shift involved.

3.2.7.2. Aurora

Following the load profiles of Janus, the ones for Aurora are conducted in a similar procedure. The major difference is imposed by the fact that all electricity generation shall be covered from renewables within the respective time frame. Hence, the most ambitious scenarios are Aurora RL10 and Aurora LS10 which foresee covering all electricity requirements from RES within 10 years.

By means of storage devices, whose size and capacity will be identified in the time series algorithm in WP4, all electricity demand shall be covered from RES and storage devices. Hence, the RES will be dimensioned to cover the annual load plus the electricity required to run the storage system. The storage system must respond to demand-supply shortages at each hour of the year as well as over the period of a whole year. For that reason a pumped-storage system is selected. In extreme cases, when there is no RES based electricity available, it will be possible to make use of still 'in range' fossil fuel units. Hence, neither the RES capacity nor storage capacity need to be oversized.

Even though there might be enough electricity generation available from fossil fuels, these units are only used for unexpected shortages. The data sets of Aurora are structured in identical format as the ones for Janus. However, the changes occur for the amount of electricity to be provided from RES and storage systems.

[27] In extreme cases, when the weather conditions prohibit electricity generation from RES, there is always the possibility to consider one of the fossil fuel units which is already considered as "phased-out". Since those units are not running on a continuous basis, it seems realistic that they have a longer lifetime and can still be used to run as emergency backup.

3.2.7.3. Antevorta

The last segment of scenario building analyses the changes undertaken in Antevorta (replacement of fossil fuels and immediate coverage from RES within time frame) along with the vector shift. Therefore, the shifting potential across all end-uses and sectors is incorporated. All vector shifting values are presented in Table 3-4 (p. 44). Table 3-9 presents the data and assumption that are applied to conduct the load profiles for Antevorta RL30 and Antevorta LS30.

It is expected that the vector shift results in noticeably higher RES requirements than in previous scenarios. At the same time a greater load shift potential may be incorporated to reflect the higher contribution of electricity in the energy portfolio; e.g. more electric vehicles and more smart electrical appliances.

The share of electricity on the total primary energy demand will also increase substantially. This is particularly noticeable in the long run where over 70% of all energy needs are supplied from RES based electricity. If other renewable energy alternatives for heat and transport fuels are considered (e.g. solar thermal and/or biofuels) then the future energy system becomes almost entirely driven by RES.

Table 3-9: Data and assumption for load profiles of Antevorta RL30 and Antevorta LS30

Input data for the creation of scenarios			Output Antevorta RL/LS 30
General data and assumptions			
Start year	-	2014	2044
Total primary energy	TJ	453,2	341,56
	GWh	125,89	94,88

1

Power unit type	Number of units	Installed capacity (MW)	Approx. full load hours (h/y) *	Capacity factor	Max full load hours (h/y) **	Annual generation (GWh/y) *	Built in	
Thermal units - diesel	1	0,50	2.000	23%	3.500	1,00	1981	phase-out
	3	3,00	2.850	33%	3.500	8,55	1999	phase-out
	4	2,20	2.468	28%	3.500	5,43	1987	phase-out
	2	1,40	1.900	22%	3.500	2,66	2007	in range
Wind	3	0,90	2.500	29%	2.500	2,25	1996	phase-out
Total		8,00				19,89		

2

Power consumption		GWh/y	19,89	31,82
Share of power on total primary energy demand		%	16%	34%
Total installed capacity		MW	8,00	
Available installed RET capacity for power generation		MW	0,90	
Available installed fossil fuel capacity for power generation		MW	1,40	
Annual energy demand	increase	%/y	1,0	
	decrease	%/y	-	
Annual power demand	increase	%/y	2,0	
	decrease	%/y	-	

3

Vector shifting	Final energy consumption by sector	Vector shifting by sector	Additional load through vector shifts
Residential	27%	80%	20,49
Commercial	14%	82%	10,89
Industry	26%	0%	0,00
Transportation	33%	19%	5,95
Power required after applying shifting potential		GWh/y	37,33
Total power after vector shift		GWh/y	69,16

4

	current		in 20 years		Saving potential by sector
Breakdown final power consumption by sector	GWh/y *	% *	GWh/y *	% *	
Residential		47,3%		51,4%	54%
Commercial		38,1%		33,3%	33%
Industry		14,1%		6,5%	0%
Transportation		0,5%		8,8%	22%
Power required after applying saving potential			GWh/y		41,02
Share of power on total primary energy demand after vector shift and applied saving potential				%	73%

5

Total power generation to be covered from RET	GWh/y	41,02
Power generation required from new RET in 10 years	GWh/y	41,02
Fossil fuel based in 10 years	GWh/y	0,00
Maximum power available from fossil fuel units	GWh/y	4,90
Peak power demand over the year	MW	6,98
Available peak power: fossil fuel capacity + baseload RET * capacity factor	MW	1,40

* Requires the information of either approx. full load hours or annual generation or percentage or annual demand

** shall determine the upper bound of full load hours under which the fossil fuel units can be operated

3.3. Determination of energy mix

As stated in Chapter 2.6 a number of energy planning tools have been created over time and they have become very sophisticated, so that often only comprehensive understanding of experts or extensive study about the procedures within the tools can get them running. Without guidance or excessive knowledge about the individual procedures it is demanding to explore the tools, all its features and the results in a way as they were intended to by the developer of the tool.

Often, it is also difficult to comprehend the procedures that are undertaken in the background to achieve the results. Since the proposed research is mainly intended for decision makers, energy planners, consultants or local energy utility managers to support them in their decision making, an algorithm is proposed that demonstrates the results and trends of each decision undertaken adequately. By following the step-by-step sequence of the algorithm any applicant can follow the changes of the system when altering any of the decision variables. This algorithm is focusing on the trends and effects of the overall system cost which is subject to the modification of any of the following decision variables: the base load RES capacities x_b, the variable RES capacities x_v, the capacity of the storage system z_1, the energy size of the storage system z_2, the initial storage level y and the adjusted average fossil fuel demand f. Even though the modeling algorithm is less accurate and humbler than many of the current state of the art tools, it presents adequate results and trends for long-term decision making.

The algorithm includes and combines many features like none of the tools reviewed in Chapter 2.6. This includes:

- the possibility of including all onshore and offshore RES,
- no pre-defined capacities of technologies,
- a reflection of costs based on the actually installed capacity along with varying cost predictions associated over time,[28]
- the effects of altering the amount of base load RES in the system,
- modifications and effects of the storage system from a system that is entirely run by RES and one storage system to one that allows for minor contributions of fossil fuels and a second storage system, and

[28] Costs are depended on the total installed capacity within the considered system. Lower costs are associated to higher unit capacities, i.e. the unit cost per MW for a 20 MW hydro power plants is cheaper than for a 5 MW unit. Besides, the effects of multiple units are reflected with lower prices, where the unit cost of one PV panel or one wind turbine is noticeably more expensive than a whole wind park or a city where several households install PV panels. For the cost classification it may also be referred to Table 3-10, where the costs changes over time are presented.

- the differences of operating the second storage system, which only interacts with fossil fuel units under unit commitment constraints, over a day and over the period of a whole year.

The proposed time series algorithm identifies all key variables along with the total system cost in a step-by-step procedure. The complexity of the algorithm evolves, as more constraints are imposed with each step. While initially the capacities for each RES are defined, in the final stages modification of the algorithm are performed to adjust the requirements of the storage system and emergency backup. Thereby, contributions from fossil fuels with respect to unit commitment constraints as well as a second storage system are introduced. The major driver for the comparison of solutions for each scenario and across all scenarios is the total system cost. A flowchart has been created to show the decisions to be made within the algorithm (Figure 3-8).

3.3.1. Cost components

The total system cost TSC is defined as the sum of all costs associated to RES, spillage, storage and, in the final stage, fossil fuels. While this research assumes some RES (biomass, geothermal and hydro energy) to serve the base load, the variable RES, storage system and thermal units cover the remaining demand.

$$TSC = \sum_{b=1}^{b_{max}} TC_{RES_b} + \sum_{v=1}^{v_{max}} TC_{RES_v} + TC_{SP}^{RES} + TC_{ST}^{RES} + TC_{FF} \qquad \text{Eq. 3-1}$$

TSC	Total system cost [$]	v_{max}	Maximum number of variable RES
TC	Total cost [$]	RES	Renewable energy sources
b	Base load RES	SP	Spillage
b_{max}	Maximum number of base load RES	ST	Storage
v	Variable RES	FF	Fossil fuel

The total cost formulation for any renewable energy technology (formulation for base load RES and variable RES is the same) is the sum of the total investment cost TIC, which is broken down into annuities over the lifetime LT of the technology, and the annual total operation and maintenance cost $TO\&MC$. The total investment cost as well as the total operation and maintenance cost of each RES also consider currently installed capacities CAP_{RES}^{old}. The new capacities for each RES CAP_{RES}^{new} need to be identified.

$$TC_{RES_b} = TIC_{RES_b} * \frac{1}{\left(\frac{1}{dis}\right) - \frac{1}{dis * (1 + dis)^{LT_{RES_b}}}} + TO\&MC_{RES_b} \qquad \text{Eq. 3-2}$$

$$TIC_{RES_b} = CAP_{RES_b}^{old} * IC_{RES_b}^{old} + CAP_{RES_b}^{new} * IC_{RES_b}^{new}$$ Eq. 3-3

$$TO\&MC_{RES_b} = CAP_{RES_b}^{old} * O\&MC_{RES_b}^{old} + CAP_{RES_b}^{new} * O\&MC_{RES_b}^{new}$$ Eq. 3-4

CAP	Capacity [MW]	$O\&MC$	Operation & maintenance cost [$/kW/y]
dis	Discount rate for RES [7%]	LT	Lifetime [years]
IC	Investment cost [$/kW]		

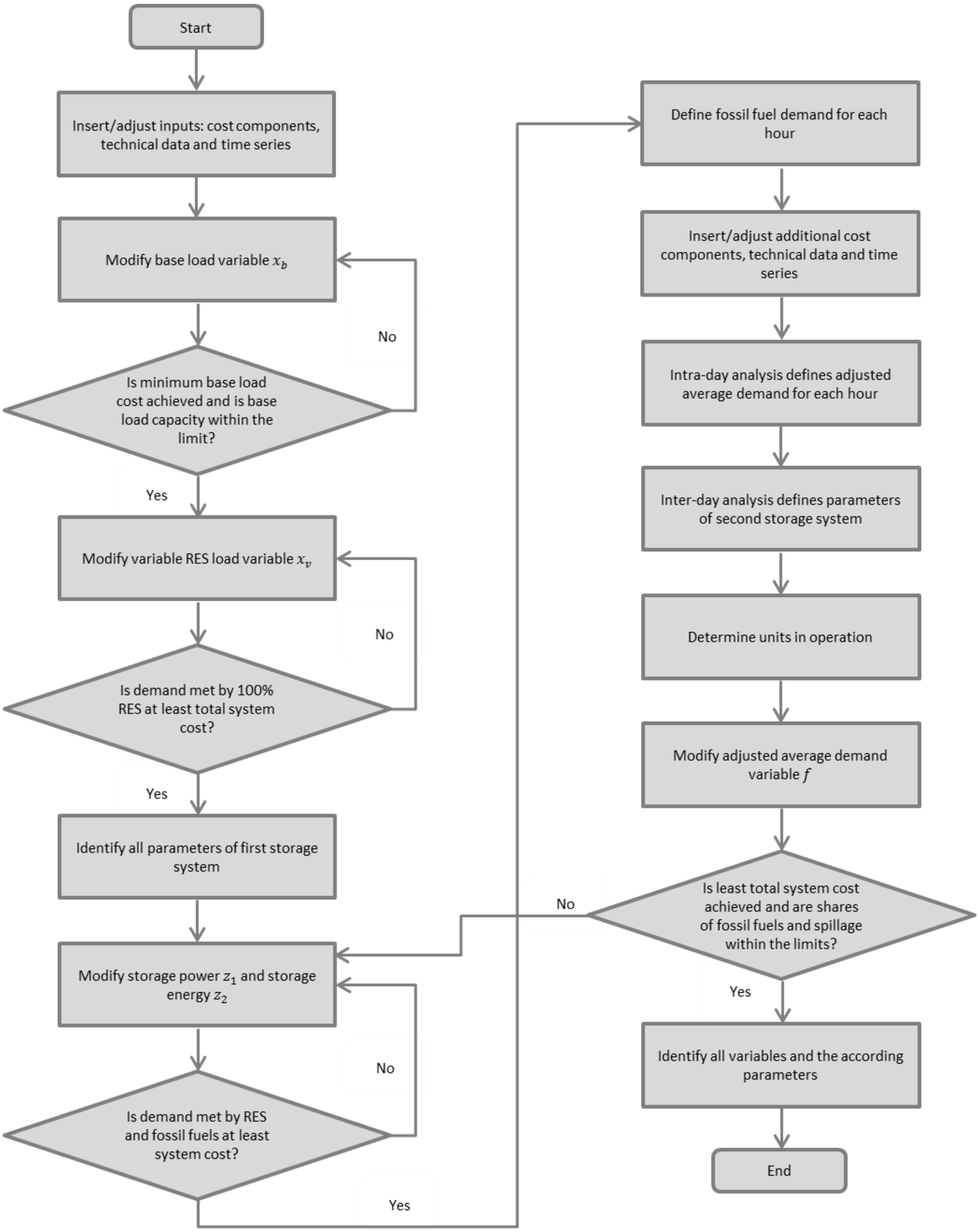


Figure 3-8: Flowchart of time series algorithm

For the time series algorithm the investment cost and operation and maintenance cost are retrieved via a look-up function from a data set. Costs for each RET change over time and based on the installed capacity. Several examples of the specific cost per kW installed, the lifetime (LT) and the typical capacity factor (CF) of each RET are presented in Table 3-10. The unit cost takes into account all these parameters to provide a benchmark for comparison with typical costs found in the literature.

Table 3-10: Changes of RET cost over time and by capacity

			Stoke boiler, Fluidized bed boiler and Combined heat and power			**Thin-film technologies**		
		CAP	IC	O&MC	Unit cost	IC	O&MC	Unit cost
		MW	$/kW	$/kW/y	$/kWh	$/kW	$/kW/y	$/kWh
10 years	below	1	**4,860**	**190.0**	0.055	**3,500**	**48.0**	0.176
		2	4,002	159.4	0.046	3,050	40.4	0.152
		5	3,144	128.8	0.036	2,600	32.7	0.128
		10	2,429	103.3	0.029	2,225	26.3	0.108
	above	20	**2,000**	**88.0**	0.024	**2,000**	**22.5**	0.096
			LT 20	CF 90%		LT 20	CF 15%	
20 years	below	1	**4,480**	**180.0**	0.051	**2,450**	**38.4**	0.119
		2	3,736	151.8	0.043	2,135	32.9	0.103
		5	2,992	123.6	0.035	1,820	27.4	0.087
		10	2,372	100.1	0.028	1,558	22.8	0.074
	above	20	**2,000**	**86.0**	0.024	**1,400**	**20.0**	0.066
			LT 20	CF 90%		LT 20	CF 16%	
30 years	below	1	**4,000**	**170.0**	0.047	**2,000**	**30.0**	0.090
		2	3,400	144.2	0.040	1,730	26.4	0.078
		5	2,800	118.4	0.033	1,460	22.8	0.066
		10	2,300	96.9	0.027	1,235	19.8	0.056
	above	20	**2,000**	**84.0**	0.023	**1,100**	**18.0**	0.051
			LT 20	CF 90%		LT 20	CF 17%	
For the cost changes over time it may be referred to the references used in Table 4-21 (p. 111) as well as the applied development trends over time according to Appendix D – Development trends and expected changes of the alternative´s attribute values over time.								

The total cost of the storage system is the sum of the annual energy discharge $ST_E^{DISCH\ RES}$ multiplied by the cost of the storage system C_{ST}^{RES}. The storage system cost is defined according to Eq. 3-6., whereas investment cost, fixed and variable operation and maintenance costs are considered. Since the storage cost is calculated in current cost values it is inflated to the start year of operation. The annual inflation rate inf is set to 2%. The storage power ST_P^{RES} and storage energy ST_E^{RES} have to be identified in the time series algorithm.

$$TC_{ST}^{RES} = \left[\sum_{i=1}^{8760} ST_{E_i}^{DISCH\ RES}\right] * \left[C_{ST}^{RES} * \left((1+inf)^t\right)\right] \qquad \text{Eq. 3-5}$$

$$C_{ST}^{RES} = \left(\frac{ST_P^{RES} * (IC_{ST} + Fixed\ O\&MC_{ST})}{\sum_{i=1}^{8760} ST_{E_i}^{DISCH\ RES}} + \frac{ST_E^{RES} * var\ O\&MC_{ST}}{\sum_{i=1}^{8760} ST_{E_i}^{DISCH\ RES}}\right) \qquad \text{Eq. 3-6}$$

C_{ST}^{RES}	Cost of RES storage [$/MWh]	$Fixed\ O\&MC$ [$/kW]	Fixed operation and maintenance cost
$ST_{E_i}^{DISCH\ RES}$	Discharged energy [MWh]		
ST_{E}^{RES}	Storage energy [MWh]	$var\ O\&MC$ [$/kWh]	Variable operation and maintenance cost
i	Hour of year [h]		
ST_{P}^{RES}	Storage power [MW]	inf	Inflation rate [2%]
IC	Investment cost [$/kW]	t	Years from now to start of project

Similar to the RETs the cost calculation of the storage system applies a look-up function. Table 3-11 and Table 3-12 list the investment cost [$/kW] and cost for the energy storage size [$/kWh] [238].

Table 3-11: Investment cost for storage unit

	MW	$/kW
below	5	3,500
	10	3,300
	25	3,000
	50	2,600
	80	2,000
	100	1,500
above	150	1,200

Table 3-12: Cost for energy storage size

	MWh	$/kWh
below	1,000	14.0
	2,000	11.2
	4,000	9.0
	8,000	7.2
above	16,000	5.7

For the spillage of each MWh a penalty of $1,000 is considered. The penalty is chosen to be several times higher than the fossil fuel generation cost, so that a minimization of spillage is encouraged. The total cost of spillage is the product of the total energy spillage per year and the cost. Costs are inflated to the start year of the considered time horizon.

$$TC_{SP}^{RES} = \left[\sum_{i=1}^{8760} SP_i^{RES}\right] * \left[C_{SP}^{RES} * ((1 + inf)^t)\right] \qquad \text{Eq. 3-7}$$

C_{SP}^{RES}	Cost of spillage [1,000 $/MWh]
SP_i^{RES}	Spillage from renewables in hour i in [MW]

The last component is the total fossil fuel cost TC_{FF}, which is the product of fossil fuel backup G_{FF} multiplied by the fossil fuel cost. No investment costs are associated since it is assumed that the fossil fuel units are already available. Two alternatives of fossil fuel generation costs are considered [239]. Costs are inflated to the start year of the considered time horizon.

$$TC_{FF} = \left[\sum_{i=1}^{8760} G_{FF_i}\right] * \left[C_{FF} * (1 + inf)^t\right] \qquad \text{Eq. 3-8}$$

C_{FF}	Cost of fossil fuels [alternative I) C_{FF} = 100 $/MWh; alternative II) C_{FF} = 150 $/MWh]
G_{FF_i}	Generation from fossil fuels in hour i in [MW]

3.3.2. Technical inputs to calculate hourly capacity factor for each RES

Based on the resource availability along with the technical inputs for each RES (Table 3-13) the hourly output value/time series is defined.

Table 3-13: Resource and technology data inputs for time series

Data	Inputs		Outputs	
Load	Hourly load data	Time series	Highest load of year (MW)	Value
			Lowest load of year (MW)	Value
			Average load over year (MW)	Value
PV	Hourly solar radiation [W/m^2]	Time series	Annual/hourly PV generation [MWh]	Value/time series
	Panel efficiency [%]	14%	Average/hourly PV capacity factor [%]	Value/time series
	Area per kW installed [m^2/kW]	9.60	Total size of PV panel [m^2]	Value
Wind	Hourly wind speed [m/s]	Time series	Annual/hourly wind generation [MWh]	Value/time series
	Technical parameters of wind turbine*	Values	Average/hourly wind capacity factor [%]	Value/time series
	Shading losses [%]	0%		
Hydro	Hourly water flow [m^3/s]	Time series	Minimum flow over year [m^3/s]	Value
	Head height [m]	20	Maximum capacity [MW]	Value
	System efficiency [%]	60%	Annual/hourly hydro generation [MWh]	Value/time series
	Reserve of flow volume [%]	10%	Average/hourly hydro capacity factor [%]	Value/time series
Biomass	Available biomass feedstock [t/y]	Value	Available biomass feedstock [t/h]	Value
	Overall efficiency [%]	30%	Maximum capacity [MW]	Value
	Targeted capacity factor [%]	80%	Annual/hourly biomass generation [MWh]	Value/time series
	Energy value [MWh/kg]	Value	Average/hourly biomass capacity factor [%]	Value/time series
Geo-thermal	Ground temperature [°C]	20	Annual/hourly geothermal generation [MWh]	Value/time series
	Geothermal temperature [°C]	180		
	Net efficiency [%]	85%	Required flow volume in [m^3/h]	Value
	Flow volume [m^3/h]	2.657	Average/hourly geothermal capacity factor [%]	Value/time series
	Typical capacity factor [%]	90%		
Offshore wind	Hourly wind speed [m/s]	Time series	Annual/hourly offshore wind generation [MWh]	Value/time series
	Technical parameters of wind turbine*	Values	Average/hourly offshore wind capacity factor [%]	Value/time series
	Shading losses [%]	0%		
Wave	Hourly wave height [m]	Time series	Hourly mean wave power [kW/m]	Time series
	Hourly wave period [s]	Time series	Annual/hourly wave generation [MWh]	Value/time series
	Approximate width of device per kW installed [m/kW]	40	Average/hourly wave capacity factor [%]	Value/time series
	Minimum wave power required for operation [kW/m]	20		
	Efficiency [%]	49%		
Tidal	Hourly tidal velocity [m/s]	Time series	Annual/hourly tidal generation [MWh]	Value/time series
	Technical parameters of tidal turbine*	Values	Average/hourly tidal capacity factor [%]	Value/time series

* Technical parameters for the designated technologies refer to power output profile of the applied device

The hourly solar output is the product of solar radiation (time series TS_{Sol_i} [W/m^2]), panel area A_{Sol} [m^2] and panel efficiency Eff_{Sol} [%]. The panel area is the product of the unit size per kW$_{el}$ A_{Sol}^{unit} [m^2/kW$_{el}$] and the total (maximum) installed capacity CAP_{Sol}^{max} [MW]. The hourly output is limited to the maximum installed capacity.

$$CAP_{Sol_i} = TS_{Sol_i} * A_{Sol} * Eff_{Sol} \quad \text{Eq. 3-9}$$

$$A_{Sol} = CAP_{Sol}^{max} * A_{Sol}^{unit} \quad \text{Eq. 3-10}$$

$$0 \leq CAP_{Sol_i} \leq CAP_{Sol}^{max} \quad \text{Eq. 3-11}$$

The hourly generation from wind is based on a look-up function, whereas the actual wind speed is associated to a power output TS_{Win_i} [kW]. An extract of the unit output (with a maximum power rating of 2,300 kW) is presented in Table 3-14.

Table 3-14: Output of wind turbine

Wind speed in m/s	Unit output in kW		Wind speed in m/s	Unit output in kW
0	0		13	2,189
3.4	0		14	2,260
3.5	0		15	2,287
3.6	0		16	2,295
3.7	0		17	2,297
3.8	0		18	2,298
3.9	0		19	2,298
4	46		20	2,300
4.1	57		21	2,300
4.2	68		22	2,300
4.3	79		23	2,300
4.4	90		24	2,300
4.5	101		25	2,300
4.6	111		26	0
4.7	122		27	0
4.8	133		28	0
4.9	144		29	0
5	155		30	0
…	…		…	…

The actual hourly output from wind CAP_{Win_i} is then subject to the number of units $units_{Win}$ and shading losses $ShaLos_{Win}$ [%] within a wind park. The formulation for onshore wind and offshore wind is identical.

$$CAP_{Win_i} = TS_{Win_i} * units_{Win} * (1 - ShaLos_{Win}) \quad \text{Eq. 3-12}$$

$$0 \leq CAP_{Win_i} \leq CAP_{Win}^{max} \quad \text{Eq. 3-13}$$

Within the proposed time series bioenergy is considered as base load. Therefore, a constant output value is defined according to:

$$CAP_{Bio_i} = CAP_{Bio} * CF_{Bio} \quad \text{Eq. 3-14}$$

$$0 \leq CAP_{Bio} \leq CAP_{Bio}^{max} \quad \text{Eq. 3-15}$$

$$CAP_{Bio}^{max} = Feed_{Bio} * Energy\ value_{Bio} * Eff_{Bio} \quad \text{Eq. 3-16}$$

Whereas,

CAP_{Bio_i}	Actual output from bioenergy is the same in all hours i [MW]
CAP_{Bio}	Defined capacity of bioenergy unit [MW]
CF_{Bio}	Targeted capacity factor for the operation of bioenergy unit [%]
$Feed_{Bio}$	Feedstock available in ton per year [t/y] (is then converted to hourly value [t/h])
$Energy\ value_{Bio}$	Energy content of feedstock [MWh/t]
Eff_{Bio}	Overall efficiency of bioenergy unit [%]

For the output from geothermal energy the flow volume FV_{Geo} [m^3/h] and temperature difference ΔT [°C] between the ground temperature and geothermal reservoir temperature are essential inputs. They define the geothermal capacity of the system, which then defines the constant hourly output CAP_{Geo_i} [MW] through the efficiency Eff_{Geo} [%] of the system.

$$CAP_{Geo_i} = CAP_{Geo} * Eff_{Geo} \quad \text{Eq. 3-17}$$

$$CAP_{Geo} = \left(\frac{(FV_{Geo} * \Delta T)}{\alpha * CF_{Geo} * ti}\right) \quad \text{Eq. 3-18}$$

$$0 \leq CAP_{Geo} \leq CAP_{Geo}^{max} \quad \text{Eq. 3-19}$$

α	Conversion coefficient from BTU to kWh, whereas 3,412 equals 1 kWh
ti	Total numbers of hours per year (8760 hours per year)
FV_{Geo}	Flow volume [m^3/h], whereas 8.33 lbs equals 1 gallon and 1 gallon equals 0.00379 m^3
CF_{Geo}	Targeted capacity factor for the operation of geothermal unit [%]

Hydro energy is another base load and therefore requires a constant hourly capacity value CAP_{Hyd_i} [MW] for the time series. The maximum hydro capacity CAP_{Hyd}^{max} [MW] is defined as:

$$CAP_{Hyd}^{max} = FV_{Hyd} * Hh_{Hyd} * Eff_{Hyd} * g * \rho_{Hyd} \quad \text{Eq. 3-20}$$

$$0 \leq CAP_{Hyd} \leq CAP_{Hyd}^{max} \quad \text{Eq. 3-21}$$

$$CAP_{Hyd_i} = CAP_{Hyd} * CF_{Hyd} \qquad \text{Eq. 3-22}$$

Whereas,

FV_{Hyd}	Flow volume [m^3/s]
Hh_{Hyd}	Head height [m]
Eff_{Hyd}	Efficiency of hydro system [%]
g	Gravity [9.81 m^2/s]
ρ_{Hyd}	Density of water [1000 kg/m^3]
CF_{Hyd}	Targeted capacity factor for the operation of hydro unit [%]

The output from wave energy devices takes into account the following formulation and constraints:

$$CAP_{Wav_i} = TS_{Wav_i} * Length_{Wav} * Eff_{Wav} \qquad \text{Eq. 3-23}$$

$$P_{Wav}^{min} \leq CAP_{Wav_i} \leq CAP_{Wav}^{max} \qquad \text{Eq. 3-24}$$

The wave power output CAP_{Wav_i} [MW] is the product of the mean wave power TS_{Wav_i} [kW/m], the length of the device $Length_{Wav}$ [m] and the system efficiency Eff_{Wav} [%]. The system only operates if the minimum mean wave power P_{Wav}^{min} [kW/m] can be reached (e.g. 20 kW/m). The output cannot be larger than the maximum of the unit power rating CAP_{Wav}^{max}.

The generation from tidal energy is calculated in a similar manner as that for wind. A look-up function is applied to identify the hourly unit output based on the tidal stream velocity. For a unit size of 500 kW the expected output is shown in Table 3-15.

The actual hourly output from tidal energy CAP_{Tid_i} is then subject to the number of units $units_{Tid}$ and net losses through caballing $NetLos_{Tid}$ [%].

$$CAP_{Tid_i} = TS_{Tid_i} * units_{Tid} \qquad \text{Eq. 3-25}$$

$$0 \leq CAP_{Tid_i} \leq CAP_{Tid}^{max} \qquad \text{Eq. 3-26}$$

In the end, the capacity of each RES in hour i can be expressed through a capacity factor CF_{RES_i}, whereas:

$$CAP_{RES_i} = CF_{RES_i}, \qquad \forall i \in [1, 8760] \qquad \text{Eq. 3-27}$$

Table 3-15: Output of tidal turbine

Tidal velocity in m/s	Unit output in kW		Tidal velocity in m/s	Unit output in kW
0	0		6	500
0,1	0		6,1	500
0,2	0		6,2	500
0,3	0		6,3	500
0,4	0		6,4	500
0,5	0		6,5	500
0,6	0		6,6	500
0,7	14		6,7	500
0,8	26		6,8	500
0,9	38		6,9	500
1	50		7	500
1,1	70		7,1	0
1,2	90		7,2	0
1,3	110		7,3	0
1,4	130		7,4	0
1,5	150		7,5	0
…	…		…	…

3.3.3. Time series algorithm

The principal time series algorithm consists of 5 consecutive steps. Each step provides outputs for the next step(s) or for the overall cost formulation (Eq. 3-1 to Eq. 3-8). Initially, all capacities of the RES are identified. Then, the storage parameters are assessed so that solutions of electricity supply based on 100% RES can be defined. Thereafter, the storage energy size and storage power are modified and spillage and backup energy in the form of fossil fuels are introduced. This 5-step algorithm does not take into account unit commitment constraints and assumes that all backup generation from fossil fuels can be provided when necessary. Only one storage system is used, which solely interacts with RES generation.

1) Identify base load capacities for all RES CAP_{RES_b}

The load that is exceeded by a distinct percentage (e.g. 90%, 80%, 70%, etc.) of the year defines the maximum base load CAP_b^{max}.[29] The actual capacity for each RES CAP_{RES_b} is the product of the capacity benchmark of that RES $CAP_{RES_b}^{Bm}$ and the variable x_b. The capacity benchmark is a pre-defined value that is determined through the natural resource availability (e.g. amount of running water or availability of feedstock) or the actual base load limit. The variable x_b ranges from 0% to 100% and is modified in 1% steps. The combination of base load technologies that satisfies the capacity limits and leads to the lowest total base load cost

[29] Initially all scenarios were calculated with the maximum base load capacity whereas the load was exceeded more than 90% of the year. However, later modifications found that the base load capacities could be increased if the resource availability for base load RES is given, mainly because the total system cost can be further reduced through less spillage and less fossil fuel backup as well as a smaller storage system.

TC_{RES_b}, defines the capacity of each base load RES. Individually and combined the capacity of all selected RES must be smaller or equal than the defined base load capacity CAP_b^{max}.

$$x_b * CAP_{RES_b}^{Bm} = CAP_{RES_b} \qquad \text{Eq. 3-28}$$

$$\sum_{b=1}^{b_{max}} CAP_{RES_b} \leq CAP_b^{max} \qquad \text{Eq. 3-29}$$

$$0 \leq CAP_{RES_b} \leq CAP_{RES_b}^{max} \leq CAP_b^{max} \qquad \text{Eq. 3-30}$$

x_b	Variable for different base load RES [%]
CAP_b^{max}	Defined base load capacity [MW]
$CAP_{RES_b}^{max}$	Defined maximum capacity for each base load RES [MW]
$CAP_{RES_b}^{Bm}$	Defined benchmark for each base load RES [MW]

2) Identify variable RES capacities $\mathrm{CAP}_{\mathrm{RES}_\mathrm{v}}$ and storage parameters

In step 2 the total demand must be met with RES and one storage system (pumped-storage). The system balances for each hour and over the course of one year are:

$$G_{RES_i} + G_{ST_i}^{RES} = D_i, \qquad \forall i \in [1, 8760] \qquad \text{Eq. 3-31}$$

G_{RES_i}	Generation from RES in hour i [MW]
$G_{ST_i}^{RES}$	Contribution of RES storage system in hour i (can be charging or discharging) [MW]
D_i	Demand in hour i [MW]

The total RES generation G_{RES_i} is the sum of base load RES generation $G_{RES_{b,i}}$ and variable RES generation $G_{RES_{v,i}}$. The actual capacity for each variable RES CAP_{RES_v} is the product of the capacity benchmark of that RES $CAP_{RES_v}^{Bm}$ and the variable x_v. The base load generation is known from step 1 and the capacity factors in each hour CF_{RES_i} are calculated according to the technical input formulations of the previous chapter.

$$G_{RES_i} = \sum_{b=1}^{b_{max}} G_{RES_{b,i}} + \sum_{v=1}^{v_{max}} G_{RES_{v,i}}, \qquad \forall i \in [1, 8760] \qquad \text{Eq. 3-32}$$

$$\sum_{b=1}^{b_{max}} G_{RES_{b,i}} = \sum_{b=1}^{b_{max}} \left(CAP_{RES_b} * CF_{RES_{b,i}}\right) \qquad \text{Eq. 3-33}$$

$$\sum_{v=1}^{v_{max}} G_{RES_{v,i}} = \sum_{v=1}^{v_{max}} \left(CAP_{RES_v} * CF_{RES_{v,i}}\right) \qquad \text{Eq. 3-34}$$

$$x_v * CAP_{RES_v}^{Bm} = CAP_{RES_v} \quad \text{Eq. 3-35}$$

$$0 \leq CAP_{RES_{v,i}} \leq CAP_{RES_v}^{max} \quad \text{Eq. 3-36}$$

For the evaluation of the contribution from variable RES the variable x_v and capacity benchmarks are introduced. The benchmark for variable RES $CAP_{RES_v}^{Bm}$ is defined by the difference of the base load limit and the peak capacity of the year. The variable x_v is given in percentage and ranges from -200% to +100%. Alterations are performed in 1% steps. Table 3-16 gives an overview of all combinations of variable RES.

Table 3-16: Alternatives of combining variable RES

Alternative		Solar	Onshore wind	Offshore wind	Wave	Tidal
1	One technology	✓				
2			✓			
3				✓		
4					✓	
5						✓
6	Two technologies	✓	✓			
7		✓		✓		
8		✓			✓	
9		✓				✓
10			✓	✓		
11			✓		✓	
12			✓			✓
13				✓	✓	
14				✓		✓
15					✓	✓
16	Three technologies	✓	✓	✓		
17		✓	✓		✓	
18		✓	✓			✓
19		✓		✓	✓	
20		✓		✓		✓
21		✓			✓	✓
22			✓	✓	✓	
23			✓	✓		✓
24			✓		✓	✓
25				✓	✓	✓
26	Four technologies	✓	✓	✓	✓	
27		✓	✓	✓		✓
28		✓	✓		✓	✓
29		✓		✓	✓	✓
30			✓	✓	✓	✓
31	Five technologies	✓	✓	✓	✓	✓

If 5 variable RES are selected than 31 alternatives may be considered. In a step-wise approach the contribution from each individual variable RES (in combination with the already defined base load) is determined. Then combinations of 2, 3, 4 and all 5 variable RES are performed so that the total cost of all RES can be defined for all 31 alternatives. The capacity of each variable

RES $CAP_{RES_{v,i}}$ must be within the limits $CAP_{RES_v}^{max}$, which is defined by either the resource availability or the benchmark.

At this point the RES generation is not curtailed and the maximum values of the storage system can be defined accordingly. The storage power ST_P^{RES} [MW] is the largest difference between demand D_i and RES generation G_{RES_i} in a specific hour of the year. The storage energy size ST_E^{RES} [MWh] is the highest state of charge $SOC_i^{RES\,max}$ [MWh] within a year. The current state of charge SOC_i^{RES} [MWh] is state of charge of the previous hour SOC_{i-1}^{RES} [MWh] plus the storage system contribution $G_{ST_i}^{RES}$ [MWh]. The storage system can be charging $ST_{E_i}^{CH\,RES}$ or discharging $ST_{E_i}^{DISCH\,RES}$. The charge and discharge conditions are presented in Eq. 43-44. A round-trip efficiency Eff_{ST}^{RES} of 75% is included in the charging condition. The hourly charge or discharge is limited to the storage power ST_P^{RES}. For the hourly state of charge SOC_i^{RES} maximum and minimum limits are imposed. The minimum state of charge $SOC^{RES\,min}$ is defined as 5% of the storage energy size ST_E^{RES} and provides a reserve margin for unexpected shortages. The maximum is the highest state of charge of the year $SOC_i^{RES\,max}$. The reserve margin was selected that small since the minimum limit is only expected to be reached for a very few times per year. Besides, novel operation modes allow for very high shares of variable RES, since the time to respond to unexpected shortages is reduced substantially [240].

$$ST_P^{RES} = max\left(D_i - G_{RES_i}\right) \qquad \text{Eq. 3-37}$$

$$ST_E^{RES} = SOC_i^{RES\,max} \qquad \text{Eq. 3-38}$$

$$SOC_i^{RES} = SOC_{i-1}^{RES} + G_{ST_i}^{RES} \qquad \text{Eq. 3-39}$$

$$G_{ST_i}^{RES} = ST_{E_i}^{CH\,RES} - ST_{E_i}^{DISCH\,RES} \qquad \text{Eq. 3-40}$$

$$\text{If } G_{RES_i} < D_i \; then \; ST_{E_i}^{DISCH\,RES} = D_i - G_{RES_i} \qquad \text{Eq. 3-41}$$

$$\text{If } G_{RES_i} > D_i \; then \; ST_{E_i}^{CH\,RES} = \left(G_{RES_i} - D_i\right) * Eff_{ST}^{RES} \qquad \text{Eq. 3-42}$$

$$0 \leq ST_{E_i}^{DISCH\,RES} \leq ST_P^{RES} \qquad \text{Eq. 3-43}$$

$$0 \leq ST_{E_i}^{CH\,RES} \leq ST_P^{RES} \qquad \text{Eq. 3-44}$$

$$SOC^{RES\,min} \leq SOC_i^{RES} \leq SOC_i^{RES\,max} \qquad \text{Eq. 3-45}$$

$$SOC^{RES\,min} = 5\% * ST_E^{RES} \quad \text{Eq. 3-46}$$

For modification purposes an initial storage level $SOC_{i=1}^{RES}$ is implemented. The variable y can be altered to define the state of charge in hour $i = 1$. This might be essential if RES generation in the initial hours of the year is very low, i.e. if a lot of PV is selected. The variable y ranges from 0% to 100%, whereas $y = 0\%$ implies that the storage is empty in hour $i = 1$. While no costs are associated to the initial storage level, the initial storage level is directly influencing the charging and discharging of the storage system as well as the spillage of RES. For that reason the initial storage level will remain zero if RES surplus can be achieved in the initial hours of the year.

$$SOC_{i=1}^{RES} = SOC_i^{RES\,max} * y \quad \text{Eq. 3-47}$$

$$0\% \leq y \leq 100\% \quad \text{Eq. 3-48}$$

At the end of step 2 all RES capacities along with their costs are defined. Besides, all storage parameters are identified. Since neither spillage nor the use of fossil fuels is considered at this stage, the storage parameters are enormous.

3) Modify storage power and introduce spillage

In step 3 a new component is added to the system. Spillage SP_i^{RES} must be added to the demand balance of Eq. 3-32.

$$G_{RES_i} + G_{ST_i}^{RES} = D_i + SP_i^{RES}, \qquad \forall i \in [1, 8760] \quad \text{Eq. 3-49}$$

All procedures presented in steps 1 and 2 remain unchanged. Only the storage power ST_P^{RES} will be reduced up to the point where demand can no longer be met and/or where the total system cost TSC reaches its minimum. Therefore, the variable z_P is introduced to obtain the modified storage power $ST_P^{RES\,mod}$.

$$ST_P^{RES\,mod} = ST_P^{RES} * (1 - z_P) \text{ until } \sum_{i=1}^{8760}\left(G_{RES_i} + G_{ST_i}^{RES}\right) \neq \sum_{i=1}^{8760}\left(D_i + SP_i^{RES}\right) \quad \text{Eq. 3-50}$$

$$and/or\ TSC_{\ z_P} = TSC_{min}$$

$$0\% \leq z_P \leq 100\% \quad \text{Eq. 3-51}$$

The cost of the storage system needs to be adjusted accordingly, whereas ST_P^{RES} needs to be replaced by $ST_P^{RES\,mod}$ in Eq. 3-6. Thereby, the contribution of the storage system $G_{ST_i}^{RES}$ might change as well.

Spillage occurs from power $SP_i^{RES\,P}$ and/or energy $SP_i^{RES\,E}$. Yet, the energy spillage is zero since the storage energy size is not modified. Though, the spillage from power is defined as:

If $\left(G_{RES_i} - D_i\right) * Eff_{ST}^{RES} > ST_P^{RES\,mod}$ then $SP_i^{RES\,P} = \left(\left(G_{RES_i} - D_i\right) * Eff_{ST}^{RES}\right) - ST_P^{RES\,mod}$ Eq. 3-52

$$SP_i^{RES} = SP_i^{RES\,P} + SP_i^{RES\,E} \quad \text{Eq. 3-53}$$

Yet $SP_i^{RES\,E} = 0$ so $SP_i^{RES} = SP_i^{RES\,P}$ Eq. 3-54

4) Modify storage energy and introduce backup from fossil fuels

Following the storage power modification now the storage energy size is reduced. Therefore, variable z_E is introduced to obtain the modified storage energy size $ST_E^{RES\,mod}$ along with all modified storage parameters (i.e. state of charge and its limits). The formulations and constraints of steps 1, 2 and 3 remain unchanged.

The system balance is extended by fossil fuel generation G_{FF_i} and the storage cost C_{ST}^{RES} takes into account the modified cost components (power, energy and the resulting changes of the storage system contribution).

$$G_{RES_i} + G_{ST_i}^{RES} + G_{FF_i} = D_i + SP_i^{RES} \quad \text{Eq. 3-55}$$

$$C_{ST}^{RES} = \left(\frac{ST_P^{RES\,mod} * (IC_{ST} + Fixed\ O\&MC_{ST})}{\sum_{i=1}^{8760} ST_{E_i}^{DISCH\,RES\,mod}} + \frac{ST_E^{RES\,mod} * var\ O\&MC_{ST}}{\sum_{i=1}^{8760} ST_{E_i}^{DISCH\,RES\,mod}}\right) \quad \text{Eq. 3-56}$$

A modification of z_E is performed until 5% of the total generation (RES plus fossil fuels) is based on fossil fuels or when the energy spillage reaches 5% of the total generation and/or when the total system cost reaches its minimum. The 5% limit for fossil fuels was chosen since it was initially proposed to cover all energy needs with RES. The small contribution of fossil fuels is introduced to demonstrate the cost differences that may be achieved when comparing a system that is 100% based on RES and one that considers small contributions of fossil fuel. The fossil fuel contribution is particularly valued to integrate variable RES and to reduce the storage requirements (mainly for energy). After varying z_E the charging $ST_{E_i}^{CH\,RES\,mod}$ and discharging $ST_{E_i}^{DISCH\,RES\,mod}$ must be reassessed.

$$ST_E^{RES\,mod} = ST_E^{RES} * (1 - z_E) \text{ until } \sum_{i=1}^{8760} G_{FF_i} \leq 5\% * \sum_{i=1}^{8760}\left(G_{RES_i} + G_{FF_i}\right)$$

$$\text{Or until } \sum_{i=1}^{8760} SP_i \leq 5\% * \sum_{i=1}^{8760}\left(G_{RES_i} + G_{FF_i}\right) \quad \text{Eq. 3-57}$$

$$and/or\ TSC_{\ z_E} = TSC_{min}$$

$$0\% \leq z_E \leq 100\% \quad \text{Eq. 3-58}$$

Then the fossil fuel backup can be determined. Fossil fuel backup G_{FF_i} is required for power $G_{FF_i}^P$ and/or energy $G_{FF_i}^E$.

$$G_{FF_i} = G_{FF_i}^E + G_{FF_i}^P, \quad \forall i \in [1, 8760] \quad \text{Eq. 3-59}$$

$$\text{If } G_{RES_i} + ST_{E_i}^{DISCH\,RES\,mod} < D_i \text{then } G_{FF_i}^E = D_i - G_{RES_i} - ST_{E_i}^{DISCH\,RES\,mod} \quad \text{Eq. 3-60}$$

$$\text{If } G_{RES_i} + ST_P^{RES\,mod} < D_i \text{ then } G_{FF_i}^P = D_i - G_{RES_i} - ST_P^{RES\,mod} \quad \text{Eq. 3-61}$$

Energy spillage occurs if the modified state of charge is full in hour $i - 1$ or the charging is greater than the difference of the modified state of charge in the previous hour and the modified maximum energy storage (maximum state of charge). Both cases imply that RES generation is greater than demand in hour i. Then Eq. 3-53 applies for the total spillage.

$$\text{If } G_{RES_i} > D_i \text{and } SOC_{i-1}^{RES\,mod} = ST_E^{RES\,mod} \text{ then } SP_i^{RES\,E} = \left(G_{RES_i} - D_i\right) * Eff_{ST}^{RES} \quad \text{Eq. 3-62}$$

$$\text{If } G_{RES_i} > D_i \text{ and } \left(G_{RES_i} - D_i\right) * Eff_{ST}^{RES} > ST_E^{RES\,mod} - SOC_{i-1}^{RES\,mod}$$

$$\text{Then } SP_i^{RES\,E} = \left(G_{RES_i} - D_i\right) * Eff_{ST}^{RES} - \left(ST_E^{RES\,mod} - SOC_{i-1}^{RES\,mod}\right) \quad \text{Eq. 3-63}$$

At the end of step 4 all RES capacities and their costs, all modified storage system parameters and its cost, energy spillage and the hourly backup from fossil fuels are identified.

5) Continue modification of storage power and energy to obtain least TSC

Step 5 performs some final adjustments of the storage parameters. All formulations and constraints of step 1 to step 4 remain unchanged. Only the variables z_P and z_E are altered so that the lowest total system cost TSC can be achieved. In this procedure, first the storage energy size ST_E^{RES} and then the storage power ST_P^{RES} are modified until the point where a further reduction of the modified storage parameters leads to higher TSC or where the demand balance or limits cannot be met (Eq. 3-50 and Eq. 3-57). Accordingly, the major outcomes from step 5 are:

$SP_i^{RES\,P}$	Spillage from RES due to power limits each hour i
$SP_i^{RES\,E}$	Spillage from RES due to energy size limits each hour i
SP_i^{RES}	Total spillage from RES in each hour i
$ST_E^{RES\,mod}$	Modified energy storage size for RES storage
$ST_P^{RES\,mod}$	Modified power of storage for RES storage
$\sum_{i=1}^{8760} ST_{E_i}^{DISCH\,RES\,mod}$	Modified discharge of RES storage in each hour i
G_{FF_i}	Total fossil fuel requirements in each hour i

3.3.4. Algorithm with unit commitment constraints

While the initial steps of the algorithm provided solutions for an electricity supply 100% RES based, the storage system was excessively large. Modifications of the storage power and energy were performed and spillage and fossil fuel backup were introduced. Yet, the considerations for the fossil fuel contribution were restricted, since the fossil fuel generation was considered as one unit that is available whenever there is a shortage. In the forthcoming algorithm more precise considerations for the operation of fossil fuel units is performed with respect to unit commitment constraints. In addition, start-up and shut down for each unit are considered. All previously defined capacities and costs for RES, the storage system that interacts with RES and the spillage that occurs from RES remain unchanged. Only the required contribution from fossil fuels will be further evaluated, whereas a second storage system, which only interacts with fossil fuel generation, will be introduced and spillage from fossil fuels will also be accounted.

3.3.4.1. Additional cost components

The initial total system cost is extended by the components resulting from fossil fuels (second storage system TC_{ST}^{FF}, spillage from fossil fuels TC_{SP}^{FF} and the actual fossil fuel cost TC_{FF}).

$$TSC = \sum_{b=1}^{b_{max}} TC_{RES_b} + \sum_{v=1}^{v_{max}} TC_{RES_v} + TC_{SP}^{RES} + TC_{SP}^{FF} + TC_{ST}^{RES} + TC_{ST}^{FF} + TC_{FF} \qquad \text{Eq. 3-64}$$

TSC	Total system cost [$]
TC	Total cost [$]
b	Base load RES
b_{max}	Maximum number of base load RES
v	Variable RES
v_{max}	Maximum number of variable RES
RES	Renewable energy sources
SP	Spillage
ST	Storage
FF	Fossil fuel

The cost of the fossil fuel storage system is defined as:

$$TC_{ST}^{FF} = \left[\sum_{i=1}^{8760} ST_{E_i}^{FF\ DISCH}\right] * [C_{ST}^{FF} * ((1 + inf)^t)] \qquad \text{Eq. 3-65}$$

$$C_{ST}^{FF} = \left(\frac{ST_P^{FF} * (IC_{ST} + Fixed\ O\&MC_{ST})}{\sum_{i=1}^{8760} ST_{E_i}^{FF\ DISCH}} + \frac{ST_E^{FF} * var\ O\&MC_{ST}}{\sum_{i=1}^{8760} ST_{E_i}^{FF\ DISCH}}\right) \qquad \text{Eq. 3-66}$$

C_{ST}^{FF}	Cost of storage [$/MWh]	$Fixed\ O\&MC$ [$/kW]	Fixed operation and maintenance cost
$ST_{E_i}^{FF\ DISCH}$	Discharged energy [MWh]		
ST_E^{FF}	Storage energy [MWh]	$var\ O\&MC$ [$/kWh]	Variable operation and maintenance cost
i	Hour of year [h]		
ST_P^{FF}	Storage power [MW]	inf	Inflation rate [2%]
IC	Investment cost [$/kW]	t	Years from now to start of project

The total cost from fossil fuel spillage is defined as:

$$TC_{SP}^{FF} = \left[\sum_{i=1}^{8760} SP_i^{FF}\right] * [C_{SP}^{FF} * ((1 + inf)^t)] \qquad \text{Eq. 3-67}$$

C_{SP}^{FF}	Cost of spillage [1,000 $/MWh]
SP_i^{FF}	Spillage in hour i in [MW]

The actual total fossil fuel cost TC_{FF} considers two components. On the one hand side, the annual fossil fuel backup $\sum_{i=1}^{8760} G_{FF_i}^{mod}$ is multiplied by the fossil fuel cost C_{FF}, whereas two alternatives of fossil fuel generation costs are considered; one high cost value of 150 $/MWh according to [239] and a conservative value of 100 $/MWh to reflect the currently low market prices. On the other hand side, the total number of start-ups TSU_{FF} is deliberated. For each start-up a fixed cost C_{SU}^{FF} is associated. Both cost components are inflated to the start year of the considered time horizon

$$TC_{FF} = \left(\left[\sum_{i=1}^{8760} G_{FF_i}^{mod}\right] * (C_{FF} * (1 + inf)^t)\right) + \left(TSU_{FF} * (C_{SU}^{FF} * (1 + inf)^t)\right) \qquad \text{Eq. 3-68}$$

C_{FF}	Cost of fossil fuels [alternative I) C_{FF} = 100 $/MWh; alternative II) C_{FF} = 150 $/MWh]
$G_{FF_i}^{mod}$	Modified generation from fossil fuels in hour i in [MW]
TSU_{FF}	Total number of start-ups for all fossil fuel units
C_{SU}^{FF}	Start-up cost [$150]

3.3.4.2. Second storage system based on fossil fuels and under unit commitment constraints

The time series algorithm continues from the initial procedures (step 5), where the demand for fossil fuel backup was defined for each hour of the year.

6) Intra-day analysis for fossil fuel generator operation

The initially defined fossil fuel generation G_{FF_i} is now declared as fossil fuel demand D_i^{FF}. Each hour i of the year (1 to 8760) can be associated to a specific hour j within day d, whereas j ranges from 1 to 24 and d from 1 to 365 (i.e. hour $j = 17$ of day $d = 23$ represents hour $i = 546$ of the year and hour $j = 4$ of day $d = 187$ represents hour $i = 4469$ of the year).

$$G_{FF_i} = D_i^{FF} = D_{j,d}^{FF} \qquad \text{Eq. 3-69}$$

Initially, it is assessed if fossil fuel generation is required and in which hour j of day d. Thereby, the operation status u of only one equivalent unit is considered and it needs to be decided if the unit is on $u_{j,d} = 1$ or off $u_{j,d} = 0$. Each $u_{j,d}$ can be associated to u_i.

$$\text{If } D_{j,d}^{FF} > 0 \text{ then } u_{j,d} = 1 \qquad \text{Eq. 3-70}$$

$$\text{If } D_{j,d}^{FF} = 0 \text{ then } u_{j,d} = 0 \qquad \text{Eq. 3-71}$$

Next, a block count c (which ranges from 1 to 24) is introduced to determine consecutive hours in which fossil fuel demand occurs. The block count starts and runs according to the following conditions:

$$\text{If } u_{j=1,d} = 1 \text{ then } c_{j=1,d} = 1 \text{ otherwise } c_{j=1,d} = 0 \qquad \text{Eq. 3-72}$$

$$\text{If } u_{j,d} = 1 \text{ and } u_{j-1,d} = 0 \text{ then } c_{j,d} = 1 \qquad \text{Eq. 3-73}$$

$$\text{If } u_{j,d} = 1 \text{ and } u_{j-1,d} = 1 \text{ then } c_{j,d} = c_{j-1,d} + 1 \qquad \text{Eq. 3-74}$$

$$\text{If } u_{j,d} = 1 \text{ and } u_{j+1,d} = 0 \text{ then } c_{j,d} = c_{j-1,d} + 1 = c_{j,d}^{max} \qquad \text{Eq. 3-75}$$

If the generator in the first hour $j = 1$ of the day is on, then the block count starts, otherwise it remains at zero (Eq. 3-72). For all hours the block count only starts if a unit is turned on in hour j, but was off in hour $j - 1$ (Eq. 3-73). The block count continues for all hours if the unit was on in j as well as in the previous hour $j - 1$ (Eq. 3-74). The highest block count is defined by the last hour a unit is turned on (Eq. 3-75).

Several blocks B_c per day may occur, whereas each $c_{j,d}^{max}$ refers to one block B_c. The fossil fuel demand is summed up for each block.

$$TD_{B_c}^{FF} = \sum_{c_{j,d}=1}^{c_{j,d}^{max}} D_{j,d}^{FF} \quad \text{Eq. 3-76}$$

Then the demand is divided in equal parts of block B_c.

$$AvD_{B_{c_{j,d}}}^{FF} = \frac{TD_{B_c}^{FF}}{c_{j,d}^{max}} \quad \text{Eq. 3-77}$$

The average demand of a block $AvD_{B_{c_{j,d}}}^{FF}$ is associated across all hours of that block. If the average demand is below the generation minimum $minG_{FF_n}$ of the smallest generation unit n, then the whole block must run at the minimum of that unit. Considerations of several units are performed in step 9.

$$\text{If } AvD_{B_{c_{j,d}}}^{FF} < minG_{FF_n} \text{ then } AvD_{B_{c_{j,d}}}^{FF} = minG_{FF_n} \quad \text{Eq. 3-78}$$

7) Intra-day constraints on fossil fuel generation

The intra-day constraints are imposed to guarantee that generation in hour $j = 1$ of each day is met and that generators may be started up in the previous hour $j - 1$ with the average demand of a block. A start-up in the previous hour is imposed if the average demand of a block does not meet the required demand in hour j.

$$\text{If } AvD_{B_{c_{j=1,d}}}^{FF} < D_{j=1,d}^{FF} \text{ then } D_{j=1,d}^{FF} = AvD_{B_{c_{j=1,d}}}^{FF^*} \quad \text{Eq. 3-79}$$

$$\text{If } c_{j,d} = 1 \text{ and } AvD_{B_{c_{j=1,d}}}^{FF} < D_{j=1,d}^{FF} \text{ then } AvD_{B_{c_{j=1,d}}}^{FF} = AvD_{B_{c_{j-1,d}}}^{FF^*} \quad \text{Eq. 3-80}$$

$$\text{If } c_{j,d} > 0 \text{ then } AvD_{B_{c_{j,d}}}^{FF} = AvD_{B_{c_{j,d}}}^{FF^*} \quad \text{Eq. 3-81}$$

The introduced constraints provide a complete overview of the adjusted average demand of block B_c in hour j of the day $AvD_{B_{c_{j,d}}}^{FF^*}$. Only in the first hour of the day, when the average generation does not meet demand, the adjusted average generation may be equal to the actual demand in hour $j = 1$.

8) Inter-day analysis of fossil fuel generation, second storage system and spillage

For the inter-day analysis the adjusted hourly average fossil fuel demand of each day j, d can be associated to the adjusted fossil fuel demand in each hour i of the year (see explanation for Eq. 3-69).

$$AvD_{B_{c_{j,d}}}^{FF^*} = AvD_i^{FF^*} \qquad \text{Eq. 3-82}$$

Since this part of the time series only analyzes the contribution from fossil fuels, RES can be omitted from the adjusted system balances.

$$G_{FF_i}^{mod} + G_{ST_i}^{FF} = D_i^{FF} + SP_i^{FF}, \qquad \forall i \in [1, 8760] \qquad \text{Eq. 3-83}$$

Henceforth, the interaction of the second storage system and the fossil fuel generation is described. The storage system charges $ST_{E_i}^{CH\,FF}$ if the adjusted fossil fuel demand $AvD_i^{FF^*}$ is greater than the actual fossil fuel demand D_i^{FF}. Since conversion losses occur for the use of the storage system, a round-trip efficiency Eff_{ST}^{FF} of 75% is considered. The additional fossil fuel demand is added to the adjusted average demand and leads to the modified fossil fuel generation in each hour $G_{FF_i}^{mod}$.

$$\text{If } AvD_i^{FF^*} > D_i^{FF} \text{ then } ST_{E_i}^{CH\,FF} = \left(AvD_i^{FF^*} - D_i^{FF}\right) + \left(AvD_i^{FF^*} - D_i^{FF}\right) * (1 - Eff_{ST}^{FF}) \qquad \text{Eq. 3-84}$$

$$\text{If } AvD_i^{FF^*} > D_i^{FF} \text{ then } G_{FF_i}^{mod} = AvD_i^{FF^*} + \left(AvD_i^{FF^*} - D_i^{FF}\right) * (1 - Eff_{ST}^{FF}) \qquad \text{Eq. 3-85}$$

The storage system discharges $ST_{E_i}^{DISCH\,FF}$ if the actual demand cannot be met with the adjusted average demand. In all hours the system discharges the adjusted average demand is equal to the modified fossil fuel generation.

$$\text{If } AvD_i^{FF^*} < D_i^{FF} \text{ then } ST_{E_i}^{DISCH\,FF} = D_i^{FF} - AvD_i^{FF^*} \qquad \text{Eq. 3-86}$$

$$\text{If } AvD_i^{FF^*} < D_i^{FF} \text{ then } G_{FF_i}^{mod} = AvD_i^{FF^*} \qquad \text{Eq. 3-87}$$

For all other conditions where demand is equal to the adjusted average demand or where the actual demand for fossil fuels is zero, the adjusted average demand is equal to the modified fossil fuel generation.

$$\text{If } AvD_i^{FF^*} = D_i^{FF} \text{ then } G_{FF_i}^{mod} = AvD_i^{FF^*} \qquad \text{Eq. 3-88}$$

$$\text{If } D_i^{FF} = 0 \text{ then } G_{FF_i}^{mod} = AvD_i^{FF^*} \qquad \text{Eq. 3-89}$$

All remaining constraints regarding the storage power, storage energy size, limits and state of charge follow the formulation of the RES storage system, which solely interacts with RES (Eq. 3-37 to Eq. 3-45). For the second storage system no lower limit for the state of charge is introduced, so that the storage can be completely discharged. No further modifications of the storage parameters are imposed.

$$ST_P^{FF} = max\left(D_i^{FF} - G_{FF_i}^{mod}\right) \quad \text{Eq. 3-90}$$

$$ST_E^{FF} = SOC_i^{FF\,max} \quad \text{Eq. 3-91}$$

$$SOC_i^{FF} = SOC_{i-1}^{FF} + G_{ST_i}^{FF} \quad \text{Eq. 3-92}$$

$$G_{ST_i}^{FF} = ST_{E_i}^{CH\,FF} - ST_{E_i}^{DISCH\,FF} \quad \text{Eq. 3-93}$$

$$0 \leq ST_{E_i}^{DISCH\,FF} \leq ST_P^{FF} \quad \text{Eq. 3-94}$$

$$0 \leq ST_{E_i}^{CH\,FF} \leq ST_P^{FF} \quad \text{Eq. 3-95}$$

$$0 \leq SOC_i^{FF} \leq SOC_i^{FF\,max} \quad \text{Eq. 3-96}$$

The fossil fuel generation causes spillage from power, energy and renewables. Spillage from renewables occurs if a generator is started up in hour i, but the actual block count only starts in the following hour.

$$SP_i^{FF} = SP_i^{FF\,P} + SP_i^{FF\,E} + SP_i^{FF\,RES} \quad \text{Eq. 3-97}$$

If $G_{FF_i}^{mod} > D_i^{FF}$ and $c_i = 0$ and $c_{i+1} = 1$ then $SP_i^{FF\,RES} = G_{FF_i}^{mod}$ Eq. 3-98

The spillages due to capacity and energy limits are defined as:

$$SP_i^{FF\,P} = \left(G_{FF_i}^{mod} - D_i^{FF}\right) * Eff_{ST}^{FF} - ST_P^{FF} \quad \text{Eq. 3-99}$$

If $SOC_{i-1}^{FF} = ST_E^{FF}$ then $SP_i^{FF\,E} = \left(G_{FF_i}^{mod} - D_i^{FF}\right) * Eff_{ST}^{FF}$ Eq. 3-100

If $\left(G_{FF_i}^{mod} - D_i^{FF}\right) * Eff_{ST}^{FF} > ST_E^{FF} - SOC_{i-1}^{FF}$ then $SP_i^{FF\,E} = \left(G_{FF_i}^{mod} - D_i^{FF}\right) * Eff_{ST}^{FF} - \left(ST_E^{FF} - SOC_{i-1}^{FF}\right)$ Eq. 3-101

9) Determination of fossil fuel units in operation

Based on the modified fossil fuel generation in each hour $G_{FF_i}^{mod}$ it shall be assessed which units operate, start-up or shut down. Each unit n is analyzed for each hour of the year, whereas minimum up time MUT_n and minimum down time MDT_n are considered for the unit operation. i_{sd} is the hour at which the unit n is shut down and i_{su} is the hour at which unit n is started up.

$$\text{If } G_{FF_i}^{mod} > 0 \text{ then } u_{n_i} = 1 \text{ for } \sum_{i=i_{su}}^{i-1} u_{n_i} < MUT_n \qquad \text{Eq. 3-102}$$

$$\text{If } G_{FF_i}^{mod} = 0 \text{ then } u_{n_i} = 0 \text{ for } \sum_{i=i_{sd}}^{i-1} (1 - u_{n_i}) < MDT_n \qquad \text{Eq. 3-103}$$

Each unit n has to operate within its minimum and maximum power output limits.

$$G_{FF_n}^{min} < G_{FF_{n_i}} < G_{FF_n}^{max} \qquad \text{Eq. 3-104}$$

The generation from all operating units must be equal or greater than the modified generation, whereby a greater generation suggests that spillage occurs.

$$\sum_{n=1}^{n} G_{FF_{n_i}} \geq G_{FF_i}^{mod} \qquad \text{Eq. 3-105}$$

A look-up function determines the status of unit n in each hour i, whereas $G_{FF_i}^{mod}$ must be within the limits of a unit combination $comb_l$ (l ranges from 1 to max) (Table 3-17). For the combination of units it is assumed that each unit can be started or shut down within one hour. Hence, the minimum up time and minimum down time are 1 hour each. The minimum capacity of a combination is the maximum capacity of the previous combination, except for $comb_{l=1}$ which is defined by the capacity of the smallest unit.

Table 3-17: Combinations of units in operation

Combination	Min capacity	Max capacity	Units operating				
			1	2	3	…	n
l_1	$minCAP_{comb_{l1}}$	$maxCAP_{comb_{l1}}$	✓			…	
l_2	$minCAP_{comb_{l2}} = maxCAP_{comb_{l1}}$	$maxCAP_{comb_{l2}}$	✓	✓		…	
l_3	$minCAP_{comb_{l3}} = maxCAP_{comb_{l2}}$	$maxCAP_{comb_{l3}}$	✓		✓	…	
…	…	…	…	…	…	…	…
l_{max}	$minCAP_{comb_{lmax}} = maxCAP_{comb_{lmax-1}}$	$maxCAP_{comb_{lmax}}$	✓	✓	✓	…	✓

$$minCAP_{comb_l} \leq G_{FF_i}^{mod} < maxCAP_{comb_l} \qquad \text{Eq. 3-106}$$

$$minCAP_{comb_{l+1}} = maxCAP_{comb_l} \qquad \text{Eq. 3-107}$$

A start up $SU_{n_i}^{FF}$ occurs if unit n is operating in hour i, but was shut down in the previous hour $i-1$. The total number of start-ups TSU_{FF} is summed up for all units and across all hours of the year.

$$\text{If } u_{n_i} > u_{n_i-1} \text{then } SU_{n_i}^{FF} = (u_{n_i} - u_{n_i-1}) = 1 \qquad \text{Eq. 3-108}$$

$$\text{If } u_{n_i} \leq u_{n_i-1} \text{then } SU_{n_i}^{FF} = 0 \qquad \text{Eq. 3-109}$$

$$TSU_{FF} = \sum_{i=1}^{8760} \sum_{n=1}^{n} SU_{n_i}^{FF} \qquad \text{Eq. 3-110}$$

10) Final modifications

The last modification of the time series algorithm is performed to meet the 5% hurdles for fossil fuel contribution and spillage at the least total system cost. Therefore, the adjusted hourly average fossil fuel demand $AvD_i^{FF^*}$ can be altered with variable f, whereas f ranges from 0% to 100%.

$$\text{Modify } AvD_i^{FF^*} * f \text{ to achieve } TSC_{min}$$

$$\text{so that } \sum_{i=1}^{8760} G_{FF_i}^{mod} \leq 5\% * \left(\sum_{b=1}^{b_{max}} G_{RES_b} + \sum_{v=1}^{v_{max}} G_{RES_v} + \sum_{i=1}^{8760} G_{FF_i}^{mod}\right) \qquad \text{Eq. 3-111}$$

$$\text{and } \sum_{i=1}^{8760} \left(SP_i^{RES} + SP_i^{FF}\right) \leq 5\% * \left(\sum_{b=1}^{b_{max}} G_{RES_b} + \sum_{v=1}^{v_{max}} G_{RES_v} + \sum_{i=1}^{8760} G_{FF_i}^{mod}\right)$$

The alteration of f might require the change of z_E (the energy size of the RES storage unit), whereas an increase of the energy size of the RES storage ST_E^{RES} is expected so that the demand for fossil fuels D_i^{FF} can be lowered in step 5. Lastly, f and subsequently z_E and z_P are altered and all formulations from step 5 onwards are repeated in a loop until the lowest total system cost TSC_{min} is determined. All constraints within these steps remain unchanged.

3.3.5. Algorithm modifications for scenarios of Janus

While for all scenarios comprising Aurora and Antevorta the time series algorithm can be applied in its entire procedure, for Janus a minor modification is essential to reflect the amount of energy that shall be covered from RES. Indeed, the annual RES generation $\sum_{i=1}^{8760} G_{RES_i}$ must exceed a pre-defined annual demand for RES $\sum_{i=1}^{8760} D_i^{RES}$. The RES demand is defined in the scenario building of WP1 (see Chapter 3.2.7.1).

$$\sum_{i=1}^{8760} G_{RES_i} \geq \sum_{i=1}^{8760} D_i^{RES} \qquad \text{Eq. 3-112}$$

Whereas $\sum_{i=1}^{8760} D_i^{RES}$ is a pre-defined share of $\sum_{i=1}^{8760} D_i$

Eq. 3-113

and $\sum_{i=1}^{8760} D_i = \sum_{i=1}^{8760}\left(D_i^{RES} + D_i^{FF}\right)$

The determination of RES capacities follows the procedures of step 1 and step 2. Thereby, the storage parameters are also assessed. The initial storage limit (Eq. 3-45 and Eq. 3-46) is not assessed in step 2, but only as part of the modifications of the average demand of each block $AvD_{B_{c_{j,d}}}^{FF}$ in step 10.

Following the modifications of z_1 and z_2 (step 3 to step 5) the hourly demand for fossil fuels D_i^{FF} is determined (Eq. 3-74). Limitations are only imposed on the amount of spillage (5%), but not on the contribution from fossil fuels (Eq. 3-65).

Hence, all procedures from step 6 to step 10 are performed accordingly (with addition of the initial storage in step 10), so that the fossil fuel unit operation as well as the second storage system can be examined. Then the total system cost TSC is assessed.

Chapter 3 provides the framework to establish future demand scenarios. Thereby, different saving and shifting measures were taken into account and two types of load profiles were created. While the regular load profile remains unchanged in its shape (for all scenarios comprising RL), load shifting (LS) was performed for the remaining scenarios. Thereby, a modified load has been created that includes time-of-use shifts for pre-defined loads according to rules. Within the time series algorithm the two different load profile types predominantly influence the base load capacity. Since the base load RES are defined in the first step all following steps are subject to changes. A total system cost comparison can then highlight the differences between the two load profile types across all scenarios. Besides, the time series algorithm provides useful information about all RES capacities, storage parameters, spillage and fossil fuel backup. Yet, the RES to be considered in the time series algorithm need to be defined, whereas Chapter 4 provides adequate decision support based on multiple conditions and criteria.

4. Decision support for technology selection

The previous chapter presented the framework to build future demand scenarios along with the mathematical formulation of the time series algorithm to match demand and supply. Within this chapter decision support is provided to identify renewable energy technologies that may be applied in the time series algorithm. Therefore, a 2-phase selection procedure is proposed. In the first phase a pre-selection of technologies according to resource availability and site characteristics takes place. Only technologies that comply with the local site conditions are considered in the second phase, where multi-criteria decision analysis is applied to all remaining technologies. The MCDA applies multi-attribute value theory, whereas users of this model have the chance to set their own criteria weights or use a reference case that will be established within this chapter.

4.1. Resource assessment and local site characteristics

Work package 2 presents a pre-selection model to identify the most suitable RETs among the various RES. Even though several RETs use the same energy source, the conditions required for the operation of a technology may differ substantially. The first phase of the selection procedure defines and evaluates the conditions for any given site location to identify the general suitability of RETs. Thereby, conditions are divided in resource availability and site characteristics. Each of the conditions is briefly explained in the forthcoming sections. Data has been collected for various onshore and offshore technologies. While onshore RES are all examined individually, for offshore RES an analysis across all technologies is attempted.

The principal condition for any RET is the resource availability. Each RES is defined by at least one condition to describe the resource availability. If the resource availability is not met, then the RET will not be considered for further analysis. In this case it would be meaningless to have favorable conditions for the site characteristics, because, in the end, it is the performance that is required to justify the costs for the installation and operation of a RET. The complete pre-selection analysis needs to be undertaken for every site location at which a RET is expected to be installed.

For all site locations where the resource availability is reached or even surpassed, several other conditions are of interest. A set of conditions to reflect the site characteristics is introduced, whereas varying quantities of conditions were identified for each RES. Even though some conditions are of greater importance than others, a minimum number of site characteristics should be met by all RETs in order to be considered for further evaluation. In fact, only if more than half and/or all exclusive conditions are met, then a RET will be assessed in the MCDA. Exclusive conditions are those site characteristics that can be identified as being noticeably more important than others. For instance, the wind speed might favor the installation of a wind turbine, but due to difficult access to the site location it is very impracticable to install a wind turbine. Likewise, it is also unlikely to install a wind turbine in a natural heritage or conservation site. In this sense various exclusive conditions were defined for almost all RES.

Lastly, a comparison across all storage technologies is undertaken, whereby different characteristics of storage technologies are examined. In order to allow for very high shares of RES in the energy mix, the time series algorithm needs to consider energy storage. Due to the services expected from a storage system, different technologies may be used for different purposes. This research intends to focus on one technology that is capable to interact with RES over short periods (hours and days), but also over longer periods (months and years). All effects of micro-, mini- and small storage devices, such as storage systems in households or electric vehicles, are not considered in this research, since the consequences of multiple storage units on the system still require further study. Indeed, it can be argued that all of these small storage units provide further backup to the overall energy system. Thus, additional reserve margin is added to the system to compensate the interaction of load and variable RES.

4.1.1. Onshore technologies

This research considers 5 onshore RES (Table 4-1) and a total of 21 renewable energy technologies (RET). The size to be considered is mini (0.1-1 MW) to small scale (1-10 MW) except for PV where micro scale appliances for rooftops are also considered. Yet, hydrogen is neglected as supply alternative due to its immaturity. Data and information about all forthcoming onshore RETs are gathered. They serve as basis for the pre-selection process.

For each RES conditions are defined to distinguish the different RETs. In the upcoming description of the pre-selection process exemplary values for the resource availability and site characteristics are applied for demonstration purposes.

Table 4-1: Overview of onshore renewable energy technologies

Technology option		RET	Examples/comments
Bioenergy	Combustion	Stoke boiler	
		Fluidized bed boiler	
		Combined heat and power (CHP)	Co-generation
		~~Co-firing~~	~~Direct co-firing, indirect co-firing, parallel co-firing~~
	Gasification	Fixed bed gasifiers	Updraft; downdraft; cross-draft
		Fluidized bed gasifiers	Circulating or bubbling bed gasifiers
		Entrained flow gasifiers	
		~~Others~~	~~Oxidation agent; heat for process~~
	Pyrolysis	Pyrolysis	Subset of gasification
	Anaerobic digestion (AD)	Anaerobic digestion	1-stage AD landfill gas, 2-stage AD, biogas upgrading
Solar	Photovoltaic	Thin-film technologies	Cu (In,Ga) Se2; CdTe; Amorphous Si:H; Nano-, micro-, poly-Si
		Emerging PV	Dye-sensitized cells; organic cells; organic tandem cells; inorganic cells; quantum dot cells
		Multi-junction Cells	Three/two-junction concentrator; three/two-junction non-concentrator
		Single-Junction GaAs	Single crystal; Concentrator; thin-film crystal
		Crystalline Si Cells	Mono-, poly-crystalline; thick Si film
	Solar thermal electricity	Parabolic Trough	Andasol 1, 2 and 3
		~~Power Tower~~	~~Planta Solar 10 and Planta Solar 20~~
		~~Dish/Engine~~	~~Maricopa Solar Project~~
		~~Updraft solar~~	~~currently no project realized~~
Onshore wind		Horizontal axis lift turbine with variable speed and gearbox	Dominating system on market
		~~Vertical axis Savonius~~	
		~~Vertical axis Darrieus~~	
Geo-thermal		Dry Steam power plants	Larderello, Geysers
		Flash steam power plants	Malitbog (Philippines)
		Binary cycle power plants	Beowawe Geothermal Facility (US)
		~~Hot rock systems~~	~~currently no commercial systems in place~~
Hydro**		Run-of-the-river	Chief Joseph Dam, Bonneville Dam
		Conventional hydroelectric	Three Gorges Dam, Itaipu Dam
		Pumped-storage	Bath County, Limberg II, Guangzhou

All technology choices that are strikethrough are not further considered within this research. This is mainly due to the inapplicability, such as for large solar thermal projects, but also due to the often early-development status

*Co-firing is not considered since it mainly takes place in combination with coal. As the target is to avoid fossil fuels and to reduce imports, co-firing will not be a feasible alternative; besides small island systems do usually not use coal power plants.

** Since hydro resources on islands are limited, the focus is placed on mini and small hydro up to a few MW. Larger projects or big dams are unlikely to be realized within a small island environment.

4.1.1.1. Bioenergy

Bioenergy is the first RES to be evaluated. Table 4-2 depicts the conditions to differentiate bioenergy technologies. The exclusive (dominant) condition that refers to the resource availability is the type of available biomass feedstock. Various classifications for biomass feedstock exist [241], [242], [243], [244]. This research differentiates 7 feedstock categories.

Table 4-2: Conditions for bioenergy resource availability and site characteristics

Conditions		Explanation	Scoring/Comments	Stoke boiler [245]	Fluidized bed boiler [245]	Combined heat and power [246]	Fixed bed gasifier [242], [247]	Fluidized bed gasifier [242], [247]	Entrained flow gasifier [242], [247]	Pyrolysis [248], [249]	Anaerobic digestion [250]
A.	Type of biomass feedstock available	Determines the type of feedstock that is available within the island energy system	Forest residues = 1;	1	1	1	1	1	1	1	
			untreated wood waste = 2;	2	2	2	2	2	2		
			crop residues = 3;			3	3	3	3		
			woody crops = 4;			4		4	4	4	
			animal waste = 5;		5						5
			industrial and municipal wastes = 6;						6	6	6
			high energy crops = 7					7	7	7	
B.	Feedstock vs. food	Assesses if growing feedstock is in competition with growing crops for food	High competition = 1; medium competition = 2; no/low competition = 3	3	3	3	3	3	3	2	1
C.	Land space availability to grow or retrieve feedstock	Defines the amount of area available to grow or to retrieve feedstock from (not required for technologies that use municipal or animal wastes)	Limited availability = 1; medium availability = 2; vast availability = 3	3	3	3	3	3	3	2	1
D.	Seasonal feedstock availability	Determines if feedstock is available on a constant basis or only for certain periods within the year	Seasonal/limited occurrence = 1; seasonal but with storage alternative =2; all year around = 3	3	3	3	3	3	3	2	2
E.	Particle size	Assesses which particle size can be used in different processes	Quantitative evaluation (mm)	6-50	<50	<72	3-15	2-10	<2	<2	N/A
F.	Moisture content (wet basis)	Assesses the moisture content to be used for processing	Quantitative evaluation (%)	10-50	<60	10-50%	<30%	<40%	<15%	10%	65-99.99
G.	Purpose	Defines the output of each process	Electricity only = 1;	1	1	1	1	1	1		
			electricity and/or heat (steam) = 2;	2	2	2	2	2	2		
			fuel = 3;							3	
			gas = 4								4

In addition to the feedstock (resource) availability a variety of other conditions are crucial site characteristics. These include the ongoing food vs. feedstock debate [251], the availability of space to grow feedstock or to retrieve feedstock from (e.g. wood from forests or agricultural residues from agricultural productivity) as well as the seasonality of feedstock [244], [252].

Other major conditions are the moisture content, the particle size as well as the purpose the final product can be used for [241], [253].

Bioenergy is of great importance for isolated areas that intend to become independent from imported fossil fuels. Especially gas or fuel generating systems hold immense value since they can provide electricity when needed the most; and thus reduce the burden of fluctuating RES such as wind and solar. Regarding the suitability of bioenergy technologies these technologies can only be applied if the feedstock vs. food condition (B.) is met. If not, then this represents another exclusive condition that would lead to the omission of a technology choice.

Table 4-2 summarizes the conditions for bioenergy technology choices. Data for a total of 8 RETs and 7 conditions is collected. The required input data consists of a value representing the resource availability and site characteristics for each condition. The pre-selection model compares the actual condition value of each RET with the resource availability and site characteristics. Binary variables are associated to each condition. If the available biomass feedstock type does not match the requirements of a certain technology choice, then this RET is excluded from further analysis. For all remaining technology choices the model analyzes the suitability for the given site characteristics. In the end, the scores of the binary variables are summed up in order to identify the RET(s) with the highest score(s). In the case of bioenergy technologies, the minimum score should be at least 4 (whereas conditions A. and B. must be met) to make sure that a technology choice is suitable under the local site conditions. For condition A. (type of feedstock) and G. (Purpose) multiple options are possible. If at least one option is met, than the binary variable becomes 1. For multiple options the sum of binary variables within one condition cannot be greater than 1 since the technology choice receives a positive score of 1 with the first match. An exemplary case for bioenergy technology choices is presented in Table 4-3. In this example all RETs are suitable in terms of resource availability. However, pyrolysis and anaerobic digestion do not meet the minimum requirements (they do not meet condition B. which is an exclusive one) and, hence, are excluded from further evaluation procedures. All other biomass RETs surpass the desired minimum score.

Table 4-3: Model for bioenergy RET pre-selection based on resource availability and site characteristics

	Resource availability and site characteristics		Stoke boiler	Fluidized bed boiler	Combined heat and power	Fixed bed gasifier	Fluidized bed gasifier	Entrained flow gasifier	Pyrolysis	Anaerobic digestion
A.	insert 1 or 0	1	1	1	1	1	1	1	1	0
	insert 2 or 0	0	0	0	0	0	0	0	0	0
	insert 3 or 0	3	0	0	1	1	1	1	0	0
	insert 4 or 0	0	0	0	0	0	0	0	0	0
	insert 5 or 0	0	0	0	0	0	0	0	0	0
	insert 6 or 0	6	0	0	0	0	0	1	1	1
	insert 7 or 0	0	0	0	0	0	0	0	0	0
B.	insert 1, 2 or 3	3	1	1	1	1	1	1	0	0
C.	insert 1, 2 or 3	2	1	1	1	1	1	1	0	0
D.	insert 1, 2 or 3	3	1	1	1	1	1	1	0	0
E.	insert 0<value<100	34	1	1	1	0	0	0	0	1
F.	insert 0<value<100	23	1	1	1	1	1	0	0	0
G.	insert 1 or 0	1	1	1	1	1	1	1	0	0
	insert 2 or 0	2	1	1	1	1	1	1	0	0
	insert 3 or 0	3	0	0	0	0	0	0	1	0
	insert 4 or 0	4	0	0	0	0	0	0	0	1
	Total		**7**	**7**	**7**	**6**	**6**	**5**	**2**	**3**

4.1.1.2. Solar

Electricity generating solar energy technologies are divided in thin film technologies (including amorphous silicon, cadmium-telluride (CdTe) and copper indium selenide/copper indium gallium selenide cells (CIS/CIGS), emerging PV cells (e.g. dye-synthesized), multi-junction cells, single-junction cells, crystalline silicon cells (monocrystalline and polycrystalline) and parabolic trough [254], [255], [256]. Other solar thermal concepts are not considered at this stage, mainly because of their size or development status. Table 4-4 shows all available technology choices along with 5 conditions that are defined for the pre-selection process. Even though solar radiation has been listed as principle condition to determine the resource availability, recent research has verified that most solar energy systems can operate under low radiation levels [257]. However, a minimum annual solar radiation is suggested with 1,000 kW/m^2 [258].[30] Other important site characteristics include the effects of shading and temperature, the required space availability, which is a direct result of the efficiency of the system, as well as the development status. Only the suggested solar radiation represents an exclusive condition. From a total of 5 conditions at least 3 (including the solar radiation) need to be met to include a RET in the further selection procedures.

[30] The solar radiation is suggested at 1,000 kW/m^2 since the model required a value to decide for the binary variable. If required, adjustments could be made, to include a technology even if the solar radiation is below the currently suggested value.

Table 4-4: Conditions for solar resource availability and site characteristics

Conditions		Explanation	Scoring/Comments	Thin-film technologies			Emerging PV [259]	Multi-junction cells	Single-junction cells	Crystalline Si-cells		Parabolic trough [260], [261]
				Amorphous Si	CdTe	CIS/CIGS				Mono-crystalline	Poly-crystalline	
A.	Solar radiation	Assesses local solar radiation	Quantitative evaluation (kWh/m^2)	preferably above 1000 kWh/m^2/year								
B.	Shading [262]	Shading limits productivity; hence, how odes the system operate	No shading = 1; partial shading = 2; lots of shading = 3	3	2	2	1	1	1	1	1	1
C.	Space/rooftop availability vs PV system size [263], [264]	Assesses the space required for the installation per kWpeak (the less required the better)	High availability = 1; medium availability = 2; limited availability = 3	1	1	1	1	3	2	2	2	1
			Quantitative evaluation (m^2/kWp)	13-20	11-13	9-11	~15-25	half of poly-crystalline (3-5)	33% more than multi-junction (5-7)	6-9	8-9	15-30
D.	Temperature influence [265], [266]	Determines how high temperatures influence the power output of the module	High influence of temperature on power output = 1; moderate influence of temperature on power output =2; low influence of temperature on power output = 3	3	3	3	2	1	2	2	1	1
E.	Development status	Defines the minimum level of development and experience with module type	Early research = 1; research and development phase = 2; well-developed = 3	2	2	2	1	1	2	3	3	2

Table 4-5: Model for solar RET pre-selection based on resource availability and site characteristics

Conditions		Scoring/Comments	Resource availability and site characteristics		Thin-film technologies			Emerging PV	Multi-junction cells	Single-junction cells	Crystalline Si-cells		Parabolic trough
					Amor-phous Si	CdTe	CIS/CIGS				Mono-crystalline	Poly-crystalline	
A.	Solar radiation	Quantitative evaluation (kWh/m^2)	insert 0<value<2,700	1,200	1	1	1	1	1	1	1	1	1
B.	Shading	No shading = 1; partial shading = 2; lots of shading = 3	insert 1, 2 or 3	2	1	1	1	0	0	0	0	0	0
C.	Space/rooftop availability vs PV system size	High availability = 1; medium availability = 2; limited availability = 3	insert 1, 2 or 3	2	0	0	0	0	1	1	1	1	0
D.	Temperature influence	High influence of temperature on power output = 1; moderate influence of temperature on power output =2; low influence of temperature on power output = 3	insert 1, 2 or 3	2	1	1	1	1	0	1	1	0	0
E.	Development status	Early research = 1; research and development phase = 2; well-developed = 3	insert 1, 2 or 3	2	1	1	1	0	0	1	1	1	1
	Total				**4**	**4**	**4**	**2**	**2**	**4**	**4**	**3**	**2**

Table 4-5 shows the solar energy model with exemplary results. By inserting the resource availability and site characteristics the model will automatically pre-select the most suitable technology choice(s). In this case, thin-film technologies, single-junction cells and crystalline silicon cells are most favorable. When inserting the inputs in the model, one must note that under greater space availability all technology choices (except multi-junction cells) would become suitable. Hence, the differentiation must associate the highest score to limited space availability, which then limits the possibilities of installing any solar system. Similar accounts for the temperature influence, which associates higher scores for lower influences. The model is formulated in a way that higher scores always include the lower ones. In that sense, the user of this model should insert the minimum or preferred conditions and characteristics. If they can be met or surpassed the technology choice receives a positive score.

4.1.1.3. Onshore wind

In spite of the fact that the horizontal axis lift turbine with variable speed and gearbox has evolved as dominating concept over the last few decades, a set of conditions is introduced to assess the resource availability and site characteristics. Obviously, it would be possible to analyze wind turbines of different scale (micro, small, large, etc.) along with their differing concepts, but at this stage of the research they are not of major interest. The focus is placed on systems in the range of 500 kW to a few MW.

Table 4-6 presents the conditions that are defined for the pre-selection of an onshore wind turbine. The conditions are then applied in the onshore wind model (see exemplary results in Table 4-7).

Table 4-6: Conditions for onshore wind resource availability and site characteristics

Conditions		Explanation	Scoring/Comments	HAWT*
A.	Wind speed	Defines the wind speed at 90m height	Quantitative evaluation (m/s)	4-24
B.	Wind occurrence	Determines the wind speed in relation to the occurrence of extreme winds and directions	Low and constant = 1; medium and variable = 2; high and irregular = 3	3
C.	Land accessibility	Access to wind turbine site location	Easy access = 1, medium access = 2; difficult access = 3	2
D.	Protected sites	Natural heritage sites or bird migration places cannot be used	No protected landscapes = 1; few protected landscapes nearby = 2; various protected landscapes = 3	1

* HAWT refers to horizontal axis wind turbine

The determining factor is the available average wind speed, which should be preferably above 6-7 m/s. The turbines operating range in this example is defined between 4 and 24 m/s. According to the wind turbine type this range can be adjusted by the user of this model. In fact, all quantitative conditions across the different RETs can be adjusted, so that the binary variable can reflect the optimal operating conditions. Among other issues are the occurrence of extreme and unsteady wind events, access to the site location and the occurrence of protected sites. In case of the latter, no wind turbine can be installed. Even if the model achieves feasible results for condition A. and B., very difficult access to the site location (C.) or the occurrence of protected sites (D.) (both with a score of 3) present a “no-go”. The thoughts within condition D. have been further extended. Users of this model will have the chance to insert either “2 no” or “2 yes”. While “2 no” means that no turbine can be installed due to protected sites, “2 yes” permits an installation of turbines either because the protected sites are very small or with enough distance to the actual site location. In case the user inserts 3 or “2 no” onshore wind turbines will be excluded from further evaluation. Within the presented example (Table 4-7) conditions A., B. and C. are met. However, the occurrence of nearby protected landscapes prevents an installation of a wind turbine.

Table 4-7: Model for onshore wind RET pre-selection based on resource availability and site characteristics

Conditions		Scoring/Comments	Resource availability and site characteristics		Wind turbine
A.	Wind speed	Quantitative evaluation (m/s)	insert 0.0<value<30.0	4.5	1
B.	Wind occurrence	Low and constant = 1; medium and variable = 2; high and irregular = 3	insert 1, 2 or 3	2	1
C.	Land accessibility	Easy access = 1, medium access = 2; difficult access = 3	insert 1, 2 or 3	2	1
D.	Protected sites	No protected landscapes = 1; few protected landscapes nearby but still possibility to install wind turbine = 2 yes; few protected landscapes nearby and therefore, no possibility to install wind turbines = 2 no; various protected landscapes = 3	insert 1, 2 yes, 2 no or 3	2 no	0
	Total				**0**

4.1.1.4. Geothermal

Geothermal technologies are divided in 3 systems. Dry steam resources are extremely rare and only the fields in Larderello in Italy, Wairakei in New Zealand and The Geysers in California are operating today. The remaining two systems (flash steam and binary cycle) differ in the operating temperature and, hence, the working fluid that is required in addition to the heat medium. Besides, flash steam can be distinguished from binary cycles due to the considerably larger unit size [267], [268], [269].

For an analysis of the different systems 7 conditions were identified (Table 4-8). Six of them are directly linked to the temperature. The geothermal gradient, resource depth and average ground temperature all lead to the actual temperature at the desired depth from which the heat shall be extracted. The derived temperature is then set in relation to the actual temperature that is required for each power plant to operate. In addition to the temperature it should be analyzed in what form the heat medium is available; as stated previously the vast majority of cases have fluids. Depending on the temperature it must then be seen if a secondary working fluid is necessary. In fact, binary cycle power plants use a working fluid which vaporizes at a much lower temperature (57 °C) than water. Lastly, it is essential to mention that the systems differ considerably in size (see condition G.). Since this research assesses small island systems, the likelihood of fitting a large flash steam power plant is limited. Instead, binary cycle power plants seem to have a suitable size as the case of São Miguel in the Azores already shows.

Table 4-8: Conditions for geothermal resource availability and site characteristics

Conditions		Explanation	Scoring/Comments	Dry steam power plant	Flash steam power plant	Binary cycle power plant
A.	Geothermal gradient	Assesses the geothermal resource condition	Quantitative evaluation (°C/100m)	value		
B.	Resource depth	How deep do you intend to drill to explore geothermal energy	Quantitative evaluation (m)	1,200-3,000		
C.	Average ground temperature	Defines average ground temperature at site location	Quantitative evaluation (°C)	value		
D.	Actual temperature at desired depth	Is the result of the actual ground temperature, the geothermal gradient and the desired resource depth	Quantitative evaluation (°C)	value	value	value
E.	Required heat medium temperature	Defines the required temperature range for power plant operation	Quantitative evaluation (°C)	150°C < T 320°C	180°C < T < 320°C	107°C < T < 182°C
F.	Heat medium and working fluid	Defines the available heat medium and if a secondary medium is required	Steam = 1; Fluid at high temperature = 2; Fluid at low to moderate temperature + secondary fluid = 3	1	-	-
				-	2	-
				-	-	3
G.	Power ratings	Shall determine the approximate required capacity range	Quantitative evaluation (MW)	34 to over 100 MW	35 to over 100 MW	1-10 MW

For the model input only 5 conditions need to be inserted (Table 4-9). Condition D. is the result of the inputs A., B. and C. Condition D. is then set in relation with E. to see if the temperature is within the desired temperature range. Again, F. is then the result of the temperature, but differentiates the available heat media.

As a consequence of the dominance of temperature related conditions it was decided that only if E., F. and G. each receive a score of 1 then the technology choice can be considered for further analysis. Hence, E., F. and G. all represent exclusive conditions. In the presented example no geothermal system meets the requirements for all conditions, either because of the temperature, the heat medium or because the usual system size was too small. The latter is a direct driver for the economic attractiveness of a project. If the required system size is too small, flash steam plants become extremely expensive. In contrast, if the desired system size becomes very bulky, then binary cycles become excessively costly.

Table 4-9: Model for geothermal RET pre-selection based on resource availability and site characteristics

Conditions		Scoring/Comments	Resource availability and site characteristics		Dry steam power plant	Flash steam power plant	Binary cycle power plant
A.	Geothermal gradient	Quantitative evaluation (°C/100m)	insert value (e.g. 2.3)		4.5		
B.	Resource depth	Quantitative evaluation (m)	insert 1,200<value<3,000		3,000	3,000	2,000
C.	Average ground temperature	Quantitative evaluation (°C)	insert value (e.g. 10.0)		15.7		
D.	Actual temperature at desired depth	Quantitative evaluation (°C)			150.7	150.7	105.7
E.	Required heat medium temperature	Quantitative evaluation (°C)			1	0	0
F.	Heat medium and working fluid	Steam = 1;	insert 1 or 0	0	0	0	0
		Fluid at high temperature = 2;	insert 2 or 0	0	0	0	0
		Fluid at low to moderate temperature + secondary fluid = 3	insert 3 or 0	3	0	0	1
G.	Power ratings	Quantitative evaluation (MW)	insert 0.0<value<100	2	0	0	1
	Total				**1**	**0**	**2**

Note: D. and E. are determined automatically based on the inputs of A., B. and C.

4.1.1.5. Hydro

For the selection of hydro technologies a more complex approach had to be chosen. In addition to the 3 technology choices (run-of-the-river, conventional hydroelectric and pumped-storage) there are also various turbine types. They can generally be divided in impulse and reaction turbines. While impulse turbines include Pelton and cross-flow turbines, reaction turbines comprise bulb, Straflo, Kaplan and Francis turbines [270]. Each turbine has its own characteristics in terms of head height and flow volume (conditions D. and E.) [89].

Initially, a location needs to be assessed in terms of its hydro availability, e.g. running river streams, running rivers with the potential to construct dams, lakes or sea. In addition, the potential for storage either in the form of natural occurring sites or probable artificial site locations need to be assessed.[31] Lastly, the seasonal occurrence of water may be considered, since it is often a crucial factor for run-of-the-river systems.

An overview of conditions is presented in Table 4-10. The possibility of storage does not apply to run-of-the-river and conventional hydroelectric plants. Since these plant types run continuously, the water flow cannot be reversed and the water cannot be stored. In addition to the different turbines their associated head heights and flow volumes have been introduced. Due to their significant head height Pelton and Francis turbines are not considered for run-of-the-river or conventional hydroelectric plants. In contrary bulb, Straflo and Kaplan turbines are not suitable for pumped-storage plants [271].

Table 4-10: Conditions for hydro resource availability and site characteristics

Conditions		Explanation	Scoring/Comments	Run-of-the-river	Conventional hydroelectric	Pumped-storage
A.	Water resource	Assesses the types of water available	Running river streams = 1; running rivers with Potential for dams = 2; Lakes = 3; Sea = 4	1	-	1
				-	2	-
				-	-	3
				-	-	4
B.	Storage possibility	Defines type of storage system available (only relevant for pumped-storage)	No storage = 1; Possibility of artificial storage = 2; Natural storage reservoirs available = 3	N/A	N/A	-
						2
						3
C.	Sea-sonality	Assesses if a system can deal with seasonal changes of water availability	Minor changes = 1; Medium changes = 2; Great changes = 3	1	2	3
D.	Head height	Defines typical head height for different turbine types - Quantitative evaluation (m)	Pelton	-	-	50<value<1,300
			Cross-flow	5<value<130	5<value<130	5<value<130
			Bulb-turbine	value<20	value<20	-
			Straflo	value<10	value<10	-
			Kaplan	20<value<40	20<value<41	-
			Francis	-	-	40<value<600
E.	Flow volume	Defines possible turbine types - Quantitative evaluation (m^3/s)	Pelton	-	-	0.5<value<50
			Cross-flow	0.5<value<5	0,5<value<5	0.5<value<5
			Bulb-turbine	3<value<500	3<value<500	-
			Straflo	value<500	value<500	-
			Kaplan	1.5<value<1,000	1.5<value<1,000	-
			Francis	-	-	1<value<1,000

Based on the provided data for each condition it was now tried to build a model that identifies the technology type along with the most suitable turbine type(s). Under condition A. and B. the user of the model has to list the available hydro resources and storage potential. Only if a technology choice has received a positive score (A. and B. (only for pumped-storage) are exclusive conditions), further evaluations take place. For run-of-the-river and conventional hydroelectric power plants the score given for storage is not applicable. Seasonality can be a

[31] Natural occurring sites should be valued higher than artificial ones. Therefore, one could think of associating higher costs to artificial sites, mainly due to the construction as well as effects on flora and fauna.

driving and influential factor for run-of-the-river power plants. However, this condition is not dominant and does not automatically lead to an exclusion of a technology choice, unless the user of this model decides to make this condition a dominant one.

Following the initial evaluation phase to determine the technology type, it is even more imperative to identify possible turbine types. Accordingly, the model´s applicant has to insert values for the head height and flow volume (both are exclusive conditions). Those values are now compared with the previously defined operating conditions of each turbine. The exemplary solution in Table 4-11 analyzes if a turbine is suitable under the current conditions. Only if head height and flow volume have both a value of 1 then a turbine becomes suitable. Under the exemplary conditions the site location is suitable for a pumped-storage system with either a Francis or Pelton turbine.

For hydro power only mini and small scale systems are considered. They typically range from some 100 kW up to around 10 MW.

Table 4-11: Model for hydro RET pre-selection based on resource availability and site characteristics

Conditions		Scoring/Comments	Resource availability and site characteristics		Run-of-the-river	Conventional hydroelectric	Pumped-storage
A.	Water resource	Running river streams = 1; running rivers with potential for dams = 2; lakes = 3; sea = 4	insert 1 or 0	1	1	0	1
			insert 2 or 0	0	0	0	0
			insert 3 or 0	3	0	0	1
			insert 4 or 0	4	0	0	1
B.	Storage possibility	No storage = 1; possibility of artificial storage = 2; natural storage reservoirs available = 3	insert 1 or 0	0	N/A	N/A	0
			insert 2 or 0	2			1
			insert 3 or 0	3			1
C.	Seasonality	Low = 1; medium = 2; high = 3	insert 1, 2 or 3	2	0	0	1
D.	Head height	Pelton	insert 0<value<1,300	50	-	-	1
		Cross-flow			1	0	1
		Bulb-turbine			0	0	-
		Straflo			0	0	-
		Kaplan			0	0	-
		Francis			-	-	1
E.	Flow volume	Pelton	insert 0<value<1,000	50	-	-	1
		Cross-flow			0	0	0
		Bulb-turbine			1	0	-
		Straflo			1	0	-
		Kaplan			1	0	-
		Francis			-	-	1
Summary		Pelton	**Summarizes all conditions and characteristics to determine the power plants and turbine type**		-	-	**1**
		Cross-flow			**0**	**0**	**0**
		Bulb-turbine			**0**	**0**	-
		Straflo			**0**	**0**	-
		Kaplan			**0**	**0**	-
		Francis			-	-	**1**

4.1.2. Offshore technologies

Amongst the various offshore RETs a total of 21 choices are considered at this stage of the research (Table 4-12). New concepts are being developed on a regular basis, especially wave and tidal stream devices. Due to the immaturity of some technologies, their lack of experience as well as their inapplicability several concepts are not considered within this research yet. These include ocean thermal energy conversion systems, salinity gradients and tidal barrage systems. Except for barrage systems which are rather irrelevant on islands, other systems could be added to the proposed model at a later stage.

It should be noted that offshore technologies have received increasing attention in recent years. A particular focus is placed on floating wind systems. Within a poll undertaken at the HUSUM 2012 62% of the participants expected floating foundations to take the lead over conventional turbine foundations in the next 20 years [272].

Table 4-12: Overview of offshore renewable energy technologies

Technology option		RET	Examples
Offshore Wind Devices	Fixed/moored devices	Monopile	Horns Ver 1 + 2
		Gravity	Nysted
		Tripod	Alpha Ventus
		Jacket	Alpha Ventus; Thornton Bank Phase II
		Bucket	DDHI Composite Bucket Foundation Test Project
	Floating	Spar-buoy	Demonstration Project – Kabashima; Hywind
		TLP	WindFloat
		Semi-Submersible	Kyushu University Wind Lens Project – phase 1
		~~Barge~~	~~not applicable~~
Wave Energy Devices		Attenuator	Pelamis; Sloped IPS Buoy
		Point absorber	Sperboy; PS Frog; SEEWEC
		Oscillating Wave Surge Converter	Oyster; Waveroller
		Oscillating water column	SEAREV; Limpet
		Overtopping/Terminator device	Mighty Whale; Wave Dragon
		Submerged pressure differential	SARAH pump; DMP device
		Rotating mass	Penguin, WE 50
		~~Bulge wave~~	~~Anaconda~~
		Others	Wave Plane; Pendulor
Tidal Energy Devices		Horizontal Axis	TiDEL; Swan Turbine
		Vertical Axis	THWAT; tidal turbine
		Oscillating hydrofoil	Stingray, SeaSnail
		Enclosed tips (venturi)	Rochester Venturi; Hydrokinetic
		Tidal kite	Deep Green
		~~Archimedes Screw~~	~~Flumill Power Tower~~
		~~Others~~	~~Hydro-gen; Red Hawk~~
		~~Barrage devices~~	~~not applicable~~

All technology choices that are ~~strikethrough~~ will not be further considered within this research. This is mainly due to the inapplicability, such as for barrage devices, but also due to early-development status.
Note: the examples listed are not necessarily the devices that represent each technology choice in the following analysis.

Following the division of various concepts in technology choices, an attempt was undertaken to evaluate all offshore technologies together. Initially, the pre-selection process assesses the resource availability of each technology choice. The conditions by RES are wind speed [m/s], mean wave power [kW/m of wave crest length] and tidal stream velocity [m/s] for wind, wave and tidal devices respectively. These three conditions are exclusive. If a technology choice does not meet the requirements, it will be excluded from any further evaluation.

Another exclusive condition, which has been applied across all offshore RETs, is the water depth. In fact, the water depth can be applied to characterize the suitability of any offshore device.

If the resource availability and water depth are met, then each technology will perform further evaluation of the site characteristics. As such the sea roughness and extreme weather conditions shall be assessed. Additionally, more technical features such as the inertia of the system, its response to aero- and hydrodynamics as well as the elasticity are evaluated. Thereafter, the soil conditions are analyzed, whereby technology choices can be suitable across various types of soils and seabed's. In a similar manner mooring dynamics need to be assessed since they possess an important role in stabilizing the system and securing it at the site location. This eventually leads to the impact of ships and ice on devices and vice versa, whereby the wave and current direction should not be underestimated. Lastly, a group of conditions related to the construction and maintenance of devices is formed. Larger technologies are often more material, human resource and time intensive. Thus, it might be necessary to have special vessels for construction or transport. All these aspects shall be reflected within these conditions. While the construction looks purely at the requirements from constructing the device until placing it at its final site location, the operation and maintenance assesses how often a device has to be maintained and how resource (materials, vessels, humans, etc.) intensive the maintenance is. As a matter of fact, devices could either be maintained at their site location or need to be towed to a nearby harbor. For that reason it is also important to understand whether or not access to the device is required throughout the year or only for limited periods. Further explanation to each condition is presented in Table 4-13 [273].

The scores associated to each condition determine or quantify the required characteristics to operate a device. Thereby, it is divided in 1, 2 and 3, whereas 1 represents the most modest conditions and 3 the harshest and most extreme conditions. Conditions that are ranked with 1 require optimal site characteristics whereas conditions ranked with 3 can also be applied at more difficult sites locations. Consequently, technologies that can cope with more difficult

Table 4-13: Conditions for offshore wind resource availability and site characteristics

	Conditions	Explanation	Scoring/Comments	Monopile	Gravity	Tripod	Jacket	Bucket	Spar	TLP	Semi-subm.
a.	Water depth	Determines the type of foundation/mooring (suitable water depth) and directly influences distance to mainland	Quantitative evaluation (m)	0-30 m	0-30 m	25-50 m	25-50 m	10-40 m	120 - 700 m	50 - 100 m	50 - 150 m
b.	Sea roughness	Considers the effects of streams, currents, irregular waves, etc. to determine a devices requirements for operation	Calm/steady = 1; Rough = 2; Very rough = 3	3	3	3	3	3	1	2	2
c.	Extreme weather conditions	Structure´s response to extreme winds, waves and currents (hurricanes); structure´s survivability under extreme environmental loading	Low survivability = 1; medium survivability = 2; high survivability = 3	2	2	3	3	2	1	2	2
d.	Gravity/Inertia	Inertia force is related to acceleration of water particles around a device → What level of inertia forces can a device tolerate?	Low inertia force = 1; medium inertia force = 2; high inertia force = 3	3	2	2	3	2	3	2	2
e.	Aerodynamics	Induction, skewed wake, dynamic stall, aerodynamic drag and lift → What are the preferred aerodynamics for the operation of a device?	Steady aerodynamics = 1; periodic aerodynamics = 2; randomly fluctuating aerodynamics = 3	2	3	3	3	2	2	3	2
f.	Hydrodynamics	Drag force (which is related to water particle velocities associated to wave and currents) and slap/slam force (particular important for monotowers) → What level of drag forces can a device endure?	Low drag force = 1; medium drag force = 2; high drag force = 3	2	2	3	3	2	1	2	3
g.	Elasticity (dynamic response)	Describes stiffness of the device (reveal how dynamically sensitive the structure is)	Low stiffness = 1; medium stiffness = 2; high stiffness = 3	1	2	3	3	2	1	2	1
h.	Soil conditions and seabed stability	Investigates seabed and behavior of soil at site (apply soil parameters) --> Which soil conditions are required to construct/moor/anchor the device?	Qualitative evaluation: Homogeneous soil (sand, soft clays) = 1; variable soils/stone mixed bottoms = 2; deep soft material = 3; rocky materials = 4	1	1	1	1	1	1	1	1
				2	2	2	2		2	2	2
					3						
				3	4					4	

Table 4-13 continued

i.	Mooring dynamics	Assesses how important moorings are for the stability and elasticity of a device	High importance = 1; medium importance = 2; low importance = 3	3	3	3	3	3	1	1	1
j.	Construction	Considers nearby harbors, technical equipment, human resources/vessels as well as time required for installation → How high is the effort to construct a device?	High effort = 1; medium effort = 2; low effort = 3	2	2	2	2	3	2	2	3
k.	Operation and Maintenance	How technology, time and human resource intensive is it to maintain a device?	Difficult to maintain = 1; medium to maintain = 2; easy to maintain = 3	2	2	2	2	2	2	2	2
l.	Access to construction site	Considers weather and technical availability; how often is access to the construction site required besides the common maintenance procedures?	All year around access = 1; regular access = 2; very limited access = 3	2	2	2	2	2	2	2	2
m.	Ship and ice impact	Considers the shipping traffic around system	High impact = 1; medium impact = 2; low impact = 3	3	2	2	2	3	2	2	2
n.	Current/wave direction	For selection of tidal stream technologies and site characteristics	Unidirectional = 1; regular changing = 2; often/irregular changing (multidirectional) = 3	3	3	2	3	3	2	3	3

conditions are automatically suitable for more modest conditions. For instance, a technology that has a ranking of 3 is also suitable at site locations with a score of 1 or 2.

Only for soil conditions the above described procedure does not apply. Here, the condition must be met by a device so that it becomes suitable. However, this is not an exclusive condition. Most wave and tidal devices are quite flexible in terms of the mooring and anchoring. In case the soil conditions cannot be met, most device developers are capable to find alternative mooring or anchoring systems. In contrast, the soil conditions are very important for fixed offshore wind turbine foundations, where the requirements should be met to place a certain foundation type.

Table 4-13 also summarizes the results of analysis for offshore wind devices, whereby the different foundation types are assessed predominantly. It was tried to set the different offshore RET in relation to one another, so that differences among the RETs of the same RES can be identified.

For wave and tidal devices the whole process was substantially more challenging. In a first phase the hundreds of devices (or concepts) had to be associated to one technology choice. Therefore, various resources from the literature have been used. While there are various alternatives to cluster devices, in this research the categorization by energy extraction method is selected.

An attempt was made to associate scores to various devices across the different RET (Table 4-14). Soon it could be realized that with today's publicly available information, a differentiation of devices becomes a major challenge. Therefore, it was decided to conduct a survey. Over 200 wave and tidal device companies, manufacturers, research laboratories, developers and experts were contacted throughout spring 2014 (February-April) (Appendix C – Offshore RET companies contacted for survey p. x ff.).

The response rate totaled around 30% after two rounds of surveys. The survey asked participants to score their device in "good faith" according to the conditions. It was agreed to keep all responses confidential. Therefore, no companies or device names will be listed in the following analysis. Instead, only one device for each technology choice is selected, based on which the evaluation procedures are undertaken. For that reason the scoring might differ from other devices of the same technology choice with which the reader is more familiar with, or which the reader expects to be different. Above all, further differentiation of the conditions is encouraging since minor dissimilarities could be represented more appropriately [274].

Table 4-14: Conditions for wave and tidal resource availability and site characteristics

Conditions		Wave devices								Tidal devices				
		Attenuator	Point absorber	Oscillating Wave Surge Converter	Oscillating water column	Overtopping/ terminator device	Submerged pressure differential	Rotating mass	Others	Horizontal Axis	Vertical Axis	Oscillating hydrofoil	Enclosed tips (venturi)	Tidal Kite
a.	Water depth	4-50	40-100	7-9	5-30	5-50	5-15	5-60	25-100	15-100	25-55	20-30	5-75	80-100
b.	Sea roughness	3	3	3	3	2	3	3	3	2	3	1-2	2	2
c.	Extreme weather conditions	3	2	3	3	2	2	3	3	3	2	2	2	2
d.	Gravity/Inertia	1	1	3	3	2	3	3	1	2	2	1	2	2
e.	Aerodynamics	2	2	1	2	2	3	3	3	3	1	2	3	3
f.	Hydrodynamics	3	2	1	3	2	2	3	2	1	1	2	1	1
g.	Elasticity (dynamic response)	1	1	3	1	2	3	3	2	1	1	2	1	1
h.	Soil conditions and seabed stability	1	1			1	1	1	1	1	1	1	1	1
		2		2	2	2	2		2	2	2			2
		3				3	3		3	3	3			3
		4			4	4	4		4	4	4	4	4	4
i.	Mooring dynamics	3	1	3	3	2	3	1	2	1	1	1	2	3
j.	Construction requirements	3	2	1	3	2	1	3	2	3	2	2	2	3
k.	Operation and Maintenance requirements	3	2	3	3	2	2	2	3	3	2	1	2	3
l.	Access to construction site	2	2	1	2	2	2	2	2	2	2	2	2	1
m.	Ship and ice impact	2	1	3	3	1	3	3	1	2	2	2	2	1
n.	Current/wave direction	2	2	1	1	3	2	3	3	3	2	3	2	3

Nonetheless, most wave and tidal devices within the same technology choice vary strongly, for which reason an individual system analysis seems useful. Alternatively, it might be reasonable to form groups based on the resource requirements and water depth under which the devices preferably operate. Such considerations have not been further advanced due to the limited time of this research.

In addition, it will be interesting to see how the offshore industry develops over the upcoming decades and if a major device or technology choice evolves from the hundreds of existing and/or new devices. At the same time, it seems very certain that the more devices can be developed to full-scale, the more information about the system behavior under real conditions can be obtained. Hence, minor differentiations between the designs become more obvious and could be scored accordingly (for instance on an extended scale).

The model for offshore technology pre-selection follows the ones presented for onshore technologies. Binary variables were applied to all conditions. Resource availability and water depth are exclusive conditions that have to be met under all circumstances. For wind foundations the soil conditions are also exclusive.

An overview of the required data input is presented in Table 4-15. Those inputs will then be compared with the RET requirements from Table 4-13 and Table 4-14. Two exemplary solutions of the model for offshore pre-selection are presented in Table 4-16 and Table 4-17.

The offshore technology pre-selection model is straightforward. If the resource availability is met, a technology choice continues the pre-selection process. Here, the first condition is the water depth, which again must be met. If so, the technology choice passes through all remaining conditions. Only for fixed wind devices the soil conditions also must be met. At the end of this sequence a total number appears, which should be preferably 10 or higher (the maximum is 14, so around 70% of conditions should be met). In the first example of the offshore RET pre-selection model (Table 4-16) the resource availability is met by nearly all technology choices; except for oscillating wave surge converters, vertical axis tidal devices and tidal kites. Based on the water depth another bunch of technology choices drops out, leaving five offshore wind, five wave and three tidal choices. Based on the final “suitability” value a differentiation of technologies is attempted. In this case, only four offshore foundations achieve a score of 10 or higher. Bucket foundations are excluded since they do not meet the soil conditions. Within the wave devices three are rated 10 or higher, and within tidal devices only one reaches more than 10 scores. Those would be the most suitable devices for the given site location. For that reason further analysis would focus on those pre-selected technologies.

Table 4-15: Input data for resource availability and site characteristics of offshore RETs

Conditions		Scoring/Comments	Resource availability and site characteristics
	Wind speed	Quantitative evaluation (m/s)	Value
	Mean wave power	Quantitative evaluation (kW/m)	Value
	Tidal stream velocity	Quantitative evaluation (m/s)	Value
a.	Water depth	Quantitative evaluation (m)	Value
b.	Sea roughness	Calm/steady = 1; Rough = 2; Very rough = 3	Insert 1, 2 or 3
c.	Extreme weather conditions	Low survivability = 1; medium survivability = 2; high survivability = 3	Insert 1, 2 or 3
d.	Gravity/inertia	Low inertia force = 1; medium inertia force = 2; high inertia force = 3	Insert 1, 2 or 3
e.	Aerodynamics	Steady aerodynamics = 1; periodic aerodynamics = 2; randomly fluctuating aerodynamics = 3	Insert 1, 2 or 3
f.	Hydrodynamics	Low drag force = 1; medium drag force = 2; high drag force = 3	Insert 1, 2 or 3
g.	Elasticity (dynamic response)	Low stiffness = 1; medium stiffness = 2; high stiffness = 3	Insert 1, 2 or 3
h.	Soil conditions and seabed stability	Homogeneous soil (sand, soft clays) = 1; variable soils/stone mixed bottoms = 2; deep soft material = 3; rocky materials = 4	Insert 1, 2, 3 or 4
i.	Mooring dynamics	High importance = 1; medium importance = 2; low importance = 3	Insert 1, 2 or 3
j.	Construction requirements	High effort = 1; medium effort = 2; low effort = 3	Insert 1, 2 or 3
k.	Operation & maintenance requirements	Difficult to maintain = 1; medium to maintain = 2; easy to maintain = 3	Insert 1, 2 or 3
l.	Access to construction site	All year around access = 1; regular access = 2; very limited access = 3	Insert 1, 2 or 3
m.	Ship and ice impact	High impact = 1; medium impact = 2; low impact = 3	Insert 1, 2 or 3
n.	Current/wave direction	Unidirectional = 1; regular changing = 2; often/irregular changing (multidirectional) = 3	Insert 1, 2 or 3

In the second example of the offshore RET pre-selection model (Table 4-17) there are several technology choices that undergo the complete pre-selection process. From the three offshore wind technologies that meet the wind speed and water depth requirements, all three also achieve a score higher than or equal to 10. However, the soil conditions for these fixed offshore wind devices are not met, which excludes all of them from further evaluation. Within tidal devices two out of four devices are rated with 11. Amongst the wave technology choices there are also 4 choices that achieve a value equal to or greater than 10. However, this time there is one technology choice (rotating mass) that even reaches a score of 13 out of 14, which makes the RET very suitable at the analyzed site location. In such a case and if the remaining RETs have scores that are 2-3 values lower, a decision maker may decide to only proceed with the top RET of that RES category.

Table 4-16: Model for offshore RET pre-selection based on resource availability and site characteristics – example 1

	Technology classification for Offshore Technologies	Offshore Resource Availability: Wind speed at 90m [m/s]	Offshore Resource Availability: Mean wave power [kW/m]	Offshore Resource Availability: Tidal stream velocity [m/s]	Offshore Resource Availability: Further selection process	Site Characteristics: a. water depth	b. sea roughness	c. extreme weather conditions	d. gravity/ inertia	e. aero-dynamics	f. hydro-dynamics	g. elasticity	h. soil conditions and seabed stability	i. mooring dynamics	j. construction	k. operation and maintenance	l. access to construction site	m. ship and ice impact	n. current/wave direction	suggested technology
		8	75	1.1		28	3	3	2	2	1	2	2	2	3	3	1	2	3	
Offshore Wind Devices	Monopile					1	1	0	1	1	1	0	1	1	0	0	1	1	1	10
	Gravity					1	1	0	1	1	1	1	1	1	0	0	1	1	1	11
	Tripod	1			yes	1	1	1	1	1	1	1	1	1	0	0	1	1	0	11
	Jacket/Lattice					1	1	1	1	1	1	1	1	1	0	0	1	1	1	12
	Bucket					1	1	0	1	1	1	1	0	0	0	0	0	0	0	0
	Spar-buoy					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	TLP	1			yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Semi-Submersible					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	~~Barge~~																			
Wave Energy Devices	Attenuator		1		yes	1	1	1	0	1	1	0	1	1	1	1	1	1	0	11
	Point absorber		1		yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Oscillating Wave Surge Converter		0		no	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Oscillating water		1		yes	1	1	1	1	1	1	0	1	1	1	1	1	1	0	12
	Overtopping/Terminator device		1		yes	1	0	0	1	1	1	1	1	1	0	0	1	0	1	9
	Submerged pressure differential		1		yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Rotating mass		1		yes	1	1	1	1	1	1	1	0	0	1	0	1	1	1	11
	~~Bulge wave~~																			
	Others		1		yes	1	1	1	0	1	1	1	1	1	0	1	1	0	1	11
Tidal Energy Devices	Horizontal Axis			1	yes	1	0	1	1	1	1	0	1	0	1	1	1	1	1	11
	Vertical Axis			0	no	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Oscillating hydrofoil			1	yes	1	1	1	0	1	1	0	1	0	0	0	1	1	1	9
	Enclosed tips (venturi)			1	yes	1	0	0	1	1	1	0	0	1	0	0	1	1	0	7
	Tidal kite			0	no	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	~~Archimedes Screw~~																			
	~~Others~~																			
	~~Barrage devices~~																			

Table 4-17: Model for offshore RET pre-selection based on resource availability and site characteristics – example 2

	Technology classification for Offshore Technologies	Offshore Resource Availability: Wind speed at 90m [m/s]	Mean wave power [kW/m]	Tidal stream velocity [m/s]	Further selection process	Site Characteristics: a. water depth	b. sea roughness	c. extreme weather conditions	d. gravity/ inertia	e. aero-dynamics	f. hydro-dynamics	g. elasticity	h. soil conditions and seabed stability	i. mooring dynamics	j. construction	k. operation and maintenance	l. access to construction site	m. ship and ice impact	n. current/wave direction	suggested technology
		8	48	3.4		38	2	1	3	3	3	1	3	1	1	1	2	3	3	
Offshore Wind Devices	Monopile	1			yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Gravity					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tripod					1	1	1	0	1	1	1	0	0	0	0	0	0	0	0
	Jacket/Lattice					1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
	Bucket					1	1	1	0	0	0	1	0	0	0	0	0	0	0	0
	Spar-buoy	1			yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	TLP					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Semi-Submersible					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	~~Barge~~																			
Wave Energy Devices	Attenuator		1		yes	1	1	1	0	0	1	1	1	1	1	1	1	0	0	10
	Point absorber		1		yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Oscillating Wave Surge Converter		0		no	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Oscillating water		1		yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Overtopping/Terminator device		1		yes	1	1	1	0	0	0	1	1	1	1	1	1	0	1	10
	Submerged pressure differential		1		yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Rotating mass		1		yes	1	1	1	1	1	1	1	0	1	1	1	1	1	1	13
	~~Bulge wave~~																			
	Others		1		yes	1	1	1	0	1	0	1	1	1	1	1	1	0	1	11
Tidal Energy Devices	Horizontal Axis			1	yes	1	1	1	0	1	0	1	1	1	1	1	1	0	1	11
	Vertical Axis			1	yes	1	1	1	0	0	0	1	1	1	1	1	1	0	0	9
	Oscillating hydrofoil			1	yes	1	1	1	0	1	0	1	1	1	1	1	0	1	1	11
	Enclosed tips (venturi)			1	yes	1	1	1	0	1	0	1	0	1	1	1	1	0	0	9
	Tidal kite			0	no	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	~~Archimedes Screw~~																			
	~~Others~~																			
	~~Barrage devices~~																			

4.1.3. Storage technologies

The selection process of storage technologies represents a major challenge. As described in Chapter 2.4 (p. 19) there are several time constraints when dealing with a high penetration of renewables. Certainly, security of supply is a criterion that should be met at all times. Nevertheless, when planning for decades ahead, it is reasonable to rely on hourly data (for consumption and/or generation). Therefore, it is decided to focus on storage systems that can respond to hourly, daily and monthly changes.

Table 4-18 gives a comprehensive overview of a variety of storage technologies and their major characteristics.[32] The decision for potential storage units was mainly driven by the suitable storage duration and power rating. Hence, hydrogen, pumped-storage or compressed air energy storage systems appear the most appropriate to deal with high demand-supply mismatches. Besides, a variety of batteries could be applicable. Recent research at MIT has resulted in a liquid metal battery which is extremely cost competitive and easily scalable to large power ratings [275]. It is foreseeable that new or modified concepts will be developed over the next decades. At the same time, drastic price declines are expected.

For the purpose of this research it is decided to focus on only one storage system – pumped-storage, whereby the actual size (both in terms of power and energy) of the system has to be defined (see Chapter 3.3. p. 56 ff.).[33] As a matter of fact, the storage unit should cope with the annual demand-supply mismatches over the period of a year, rather than the short-term. Power system aspects such as grid stability or fault-ride through are not considered in the analysis since they are predominantly important for short-term control services.

Depending on the local natural conditions and resource availability pumped hydro storage presents a great alternative for short and long-term energy storage. On islands with adequate altitude for the upper storage reservoir pumped hydro storage becomes even more interesting, whereby water from natural or artificial lakes or the sea could be used. The case of El Hierro (Canary Islands) demonstrates how a storage system in combination with RES can help reducing the dependency on fossil fuel backup noticeably. Additional small scale storage devices, mainly batteries in households or electric vehicles, can provide further backup for the integration of RES. Though, the effects of multiple storage systems will not be analyzed within this research.

[32] Grey colored fields in Table 4-18 are left empty since no adequate data could be found in the listed references.

[33] All aspects of micro-storage units, such as in households or small businesses, are not considered. Even the storage capacity of electric vehicles is not included in the storage size calculation.

Table 4-18: Characteristics of various storage technologies [276], [142], [275], [277], [278]

Technology classification for Storage Technologies		Characteristics: Power rating (MW)	Energy rating	Suitable storage duration	Availability	System life time (years)	Cycles	(Round-trip) Efficiency (%)	Self-discharge (%/day)	Gravimetric energy density (Wh/kg)	Volumetric energy density (Wh/L)	Start up/response times	Technological maturity (1=low, 5=high)	Power cost €/kW	Energy Cost €/kWh
Chemical	Hydrogen (fuel cells)	0,001-50	s-24h+	h-mo	90%	5-15	10^3+	20-50	0,5-2	600-1200	500-3000	min	2	550-1600	1-15
Electro-chemical	Sodium-Sulfur Battery (NaS)	0,5-50	s-h	s-h	99.98%	10-15	2000-4500	85-90	20	150-240	150-240	imediately	4	700-2000	200-900
	Sodium-Nickel-Chloride Battery (Molten Salt/Zebra)	0,001-1	min-h	s-h	99,9%+	10-14	2500+	90	15	100-140	150-280	imediately	4	100-200	70-150
	Lead-Acid Battery	0-20	s-h	min-d	99.997%	5-15	500-1000	70-80	0,1-0,3	50-80	50-80	imediately	5	$300-600	$200-400
	Palladium-acid (Pd) battery	0,001-50	s-3h			3-15	100-1000	60-95	0,1-0,3			imediately		200-650	50-300
	Nickel-Cadmium Battery	0,001-40	s-h	min-d	99%+	15-20	1000-3000	60-91	0,2-0,6	50-75	60-150	imediately	4	350-1000	200-1000
	Lithium-Ion Battery	0,001-40	min-h	min-d	97%+	5-15	10^3-10^4	85-100	0,1-0,3	75-250	200-600	imediately	4	700-3000	200-1800
	Vanadium Redox (VRB)	0,03-7	s-10h	h-mo	96-99%	5-20	10^4+	85	0-10	10-75	15-33	ms	3	2500	100-1000
	Zinc-Bromine (Zn/Br) Redox	0,05-2	s-10h	h-mo	94%	5-10	2000+	70-75	1	60-85	30-60	ms	2	500-1800	100-700
Electrical	Capacitor	0-0,05	ms-h	s-h		5	50000	60-70	40						
	Supercapacitor	0,01-1	ms-1h	s-h	99,9%+	20+	10^4-10^8	85-98	2-40	0,05-30	100.000+	ms	3	100-400	300-4000
	Superconducting magnetic energy storage (SMES)	0,01-10	ms-5min	min-h	99,9%+	20	$1*10^4$	95	10-15	0,5-5	0,2-2,5	ms	3	100-400	700-7000
Mechanical	Pumped hydro-storage (PHS)	100-5000	1-24h+	h-mo	95%+	50-100	$2*10^4$ - $5*10^4$	78-85	0	0,5-1,5	0,5-1,5	s-min	5	500-3600	60-150
	Compressed air energy storage (CAES)	100-300	1-24h+	h-mo	65-96%	25-40	$5*10^3$ - $2*10^4$	42-54	0	30-60	3-6	5-15min	5	400-1150	10-120
	Flywheel energy storage	0,002-20	15s-15min	s-min	99,9%+	20+	10^5-10^7	85-95	20-100	5-130	20-80	s	4	100-300	1000-3500
Thermal	Aquiferous low temperatur energy storage	0-5	1-8h	min-d	90%	10-20	N/A	40-60	0.5	80-250	50-500		3-4		$20-50
	High-temperatur thermal energy storage	0-60	1-24h+	min-mo		5-15	N/A	30-60	0,5-1						$30-60
	Cryogenic thermal energy storage	0,1-300	1-8h	min-d		20-40	N/A	50-60	0,05-1					$200-300	$3-30

4.2. Technology selection

With the purpose of identifying the most adequate RETs for the time series algorithm in WP4, multi-criteria decision analysis will be applied to all pre-selected RETs. Multi-attribute value theory was selected. Since the scenarios span across a period of 30 years, changes in the attributes of each technology (alternative) and criterion are considered over time. Therefore, expected learning curves and trends are applied to make future predictions about each attribute.

4.2.1. Multi-attribute problem

In order to support decision makers (DMs) with improving the quality of their decision making, three different approaches can be defined. Normative models suggest *"how people should make inferences and decisions"*. Descriptive models designate *"how people do make inferences and decisions"*. Both models contribute to prescriptive decision analyses, which *"seek to guide decision makers towards the ideal encoded by normative theories within the context of a real, often ill-defined problem, mindful of their cognitive characteristics"* [279].

Combinations of strategies are regularly applied by decision makers when making a decision [280]. In complex situations DMs are more likely to use non-compensatory strategies to reduce the initial choice set [281]. However, this might lead to the danger of suboptimal decisions. Therefore, Keeney suggests prescriptive decision analysis, which should follow value-focused thinking [282].

DMs are usually confronted by several conflicting objectives. Thus, DMs must balance the objectives in their choice of action. On the one hand, there are criteria, which express specific factors that need to be considered in a decision. On the other hand, there are objectives. They can be described as a criterion plus a direction of preference. Objectives maximize or minimize a certain factor [283].

In order to be useful, criteria must meet several requirements: they *"must be measurable, either objectively, judgmentally or by proxy"*, they *"should not measure the same aspect of the model"* and they *"should distinguish between consequences, otherwise they are redundant and should not be included in the analysis* [283]*"*.

This research follows standard decision theory, whereas the Neumann-Morgenstern axioms are valid [284]:

- If Z is a subset of R_r and

- $A_1 \geq A_2$ and $A_1 \neq A_2 \Rightarrow A_1 \succ A_2$ for all $A_1, A_2 \in Z$
- For all $A_1, A_2, A_3 \in Z$ such that $A_1 \succ A_2 \succ A_3$, it exists exactly one $\lambda \in (0,1)$ such that $A_2 \sim [\lambda . A_1 + (1-\lambda). A_3]$

- Then, it exists a real value function $v()$ such that
  - $A_1 \succ A_2 \Leftrightarrow v(A_1) > v(A_2)$
  - $A_1 \sim A_2 \Leftrightarrow v(A_1) = v(A_2)$

When dealing with multi-attribute problems (Table 4-19), decision makers analyze a finite, discrete set of alternatives $A = A_1, A_2, \dots A_r$. The maximum number of alternatives A_r depends on the pre-selection of RETs in WP2 (Chapter 4.1). In order to reflect the concerns of decision makers, alternatives may be ranked or sorted according to a set of criteria $c = c_1, c_2, \dots c_q$. This research considers 9 criteria as described in Table 4-20. Each criterion must be real-valued [283].

Table 4-19: Multi-attribute problem in matrix format

		Criteria			
		c_1	c_2	…	c_q
Alternatives	A_1	a_{11}	a_{12}	…	a_{1q}
	A_2	a_{21}	a_{22}	…	a_{2q}
	…	…	…	…	…
	A_r	a_{r1}	a_{r2}	…	a_{rq}

Table 4-20: Criteria and description

Criteria	Description
Capacity factor (CF) [%]	Assesses the ratio of the actual power output of a unit over a period of time (typically one year) to the units potential output (basically a continuous operation over the same time period).
Reliability (REL) [%]	Describes the capability of the technology to perform as designed. It also demonstrates the technology resilience.
Investment cost (IC) [$/kW$_{el}$]	Compiles all costs that can be associated to the start-up of a project. Therefore, equipment purchases, legal authorizations, road and/or grid connections, etc. have to be related. Decommissioning costs might also be incorporated.
Operation and maintenance cost (O&MC) [$/kW/y]	Are the costs that occur during the operation of the system; such as system operation and maintenance, salaries, etc.
Lifetime (LT) [years]	Is defined by the expected time of service of a RET system.
Life cycle CO_2 emissions ($LCCO_2E$) [gCO_2/kWh_{el}]	Are the specific greenhouse gas emissions (or CO_2 emissions) of all energy and material flows of construction, operation and demolition of the power system.
Land use (LU) [m^2/kW]	Refers to the area required for RET projects.
Job creation (JC) [#/MW]	Considers the number of people that are employed during the life cycle of an energy project; mainly for construction, operation and maintenance as well as decommissioning of the project.
Public acceptance (PA) [-]	Refers to the local population´s acceptance or opinion towards certain technologies. As public acceptance is not measurable a qualitative scoring is essential.

The Neumann-Morgenstern axioms establish the conditions necessary to allow for the use of value functions. Additive value functions can only be applied, if all criteria are judged as preferentially independent by the DM. Within this multi-attribute problem the preferences are as follows:

- All other things being equal, greater capacity factor (CF) is preferred to lower.
- All other things being equal, more reliability (REL) is preferred to less.
- All other things being equal, less investment cost (IC) is preferred to more.
- All other things being equal, less operation and maintenance cost (O&MC) is preferred to more.
- All other things being equal, longer lifetime (LT) is preferred to shorter.
- All other things being equal, less life cycle CO_2 emission ($LCCO_2E$) is preferred to more.
- All other things being equal, less land use (LU) is preferred to more.
- All other things being equal, more job creation (JC) is preferred to less.
- All other things being equal, more public acceptance (PA) is preferred to less.

If for any alternative A_r ($r \in [1 \dots r_{max}]$) and criterion c_q ($q \in [1 \dots q_{max}]$) the value function score of an attribute $v_q(a_{rq})$ as well as the criteria weights w_q are defined, an overall value function $v(A_r)$ may be applied. Therefore, additive value functions can be used, whereas the value function scores of attributes and the criteria weights need to be aggregated.

$$v(A_r) = \sum_{q=1}^{q_{max}} w_q v_q(a_{rq}) \qquad \text{Eq. 4-1}$$

Linear value functions are built, where $v_q(a_{rq})$ represents the value function for a specific criterion of alternative $\mathrm{A_r}$. Each individual value function measures the satisfaction of one criterion without taking into account the value of the other criteria. Value functions can either be minimized (investment cost, operation & maintenance cost, life cycle CO_2 emissions and land use) (Eq. 4-2) or maximized (capacity factor, reliability, lifetime, job creation and public acceptance) (Eq. 4-3).

$$v_q(a_{rq}) = \frac{a_q^{max} - a_{rq}}{a_q^{max} - a_q^{min}} \qquad \text{Eq. 4-2}$$

$$v_q(a_{rq}) = \frac{a_{rq} - a_q^{min}}{a_q^{max} - a_q^{min}} \qquad \text{Eq. 4-3}$$

In addition to linear value functions, DMs may also apply non-linear value functions to reflect the variation of satisfaction in the range of attributes. The convex value function curves are particularly interesting, if DM´s want to avoid bad outcomes, keep close to good outcomes or, simply, when they want to take into consideration that an increase/decrease towards the best or worst outcome has less/more influence on a decision Figure 4-1 [285].

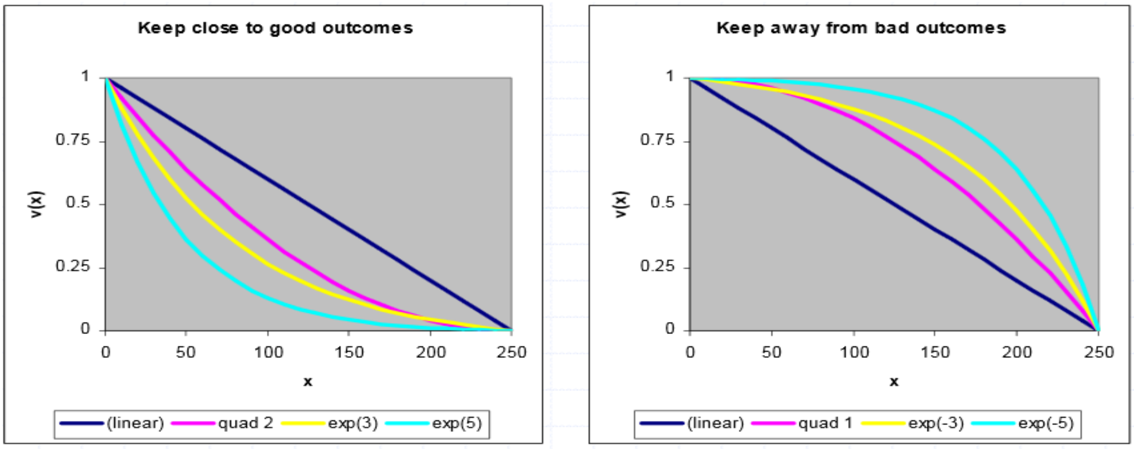


Figure 4-1: Different possibilities of value functions

In order to reflect the DMs preferences on criteria, importance weights or swing weights can be applied. Swing weights are selected for this research, since they are based on the importance and variation of the scales of the attributes. In contrast, importance weights do not reflect the variation of the attributes range.

Initially, the swing weight method defines the worst outcomes on all criteria for one alternative. Then, the DM is asked to change the most valued criterion from worst to best and associates a maximum weight of 100. In this manner, the DM defines the improvements of each criterion by 'swinging' from worst to best. Thereafter, the criteria can be sorted according to the greatest improvements. Each 'swing' can be expressed in proportion of the most preferred swing [286]. The major benefit of this method is the consideration of the ranges of attributes.

Once weights have been associated to all criteria, the unnormalized weights m_q are defined. The weights are then normalized according to:

$$w_q = \frac{m_q}{\sum_{q=1}^{q_{max}} m_q} \qquad \text{Eq. 4-4}$$

The normalization of all criteria weights adds up to 1.

$$\sum_{q=1}^{q_{max}} w_q = 1 \qquad \text{Eq. 4-5}$$

4.2.2. Data sets for attributes of each alternative and results

Attributes for each RET (each RET represents one alternative) were gathered. Due to the variety of references and owing to the size and features of each RET the attributes of a specific alternative and criterion might be represented in ranges (Table 4-21). In this case the data needs to be adjusted. Therefore, the average values of ranges are formed and rounded to full numbers (except for public acceptance, where values will be rounded to each 0.5 decimal).

Table 4-21: Data set for each attribute by RET

RET	CF (%)	REL (%)	IC ($/kW$_{el}$)	O&MC ($/kW/y)	LT (years)	LCCO$_2$E (gCO_2/ kWh$_{el}$)	LU (m^2/kW)	JC (#/MW)	PA (-)
Stoke boiler	90%	90-95+%	2,000-5,400	90-200	20	9-118	5,000	4	4-6
Fluidized bed boiler	90%	93-98%	2,000-5,400	90-200	20	9-118	5,000	4	4-6
Combined heat and power (CHP)	90%	70-85%	2,000-5,400	90-200	20	25-130	5,000	4	4-6
Fixed bed gasifiers	90%	80-90%	3,600-6,400	90-200	20	35-99	5,000	4	4-6
Fluidized bed gasifiers	90%	up to 98%	3,600-6,400	90-200	20	35-99	5,000	4	4-6
Entrained flow gasifiers	90%	80%	3,600-6,400	90-200	20	35-99	5,000	4	4-6
Pyrolysis	85-90%	90%	1,500-2,500	90-200	20	35-99	5,000	25	4-6
Anaerobic digestion	91%	70-90%	2,900-7,700	90-200	15-25	35-99	5,000	25	4-6
Thin-film technologies	12-15%	93.5-99%	3,400-5,900	25-60	25	19-70	35-120	35	7.5-8.5
Emerging PV	10-12%	93.5-99%	3,400-5,900	25-60	25	29-80	35-120	35	7.5-8.5
Multi-junction Cells	20-25%	93.5-99%	3,400-5,900	25-60	25	29-80	35-120	35	7.5-8.5
Single-Junction GaAs	15-20%	93.5-99%	3,400-5,900	25-60	25	43-62	35-120	35	7.5-8.5
Crystalline Si Cells	14-18%	93.5-99%	3,400-5,900	25-60	25	19-70	35-120	35	7.5-8.5
Parabolic Trough	56%	92-94%	6,000-10,000	60-63	30	14-32	80	5.7	7.5-8.5
Horizontal axis lift turbine	25-45%	98%	1,800-2,200	25	20	7-56	790	13	5.5-7.5
Dry Steam power plants	90+%	92-99%	2,500	80-120	27,5	38	18-30	4-17	4-7
Flash steam power plants	90+%	92-99%	2,900	100-220	27,5	38-79	18-30	4-17	4-7
Binary cycle power plants	90+%	80%	4,000	95-210	30	20-57	18-30	4-17	4-7
Run-of-the-river	40-95%	50-98%	1,400-3,700	15-85	40-80	2-5	130-750	18,6	6-8
Conventional hydroelectric	30-60%	90-95%	1,400-3,700	15-85	40-80	2-9	130-750	18,6	6-8
Pumped-storage	10-30%	up to 99%	1,400-3,700	15-85	40-80	11-20	130-750	18,6	6-8
Monopile	30-45%	98%	3,500	100-160	20	8-35	790	15-25	5.5-7.5
Gravity	30-45%	98%	3,500	100-160	20	8-35	790	15-25	5.5-7.5
Tripod	30-45%	98%	3,500	100-160	20	8-35	790	15-25	5.5-7.5
Jacket	30-45%	98%	3,500	100-160	20	8-35	790	15-25	5.5-7.5
Bucket	30-45%	98%	3,500	100-160	20	8-35	790	15-25	5.5-7.5
Spar-buoy	37-50%	98%	4,200	100-160	20	8-35	790	15-25	7-8.5
TLP	37-50%	98%	4,200	100-160	20	8-35	790	15-25	7-8.5
Semi-submersible	37-50%	98%	4,200	100-160	20	8-35	790	15-25	7-8.5
Attenuator	22-31%	88%	5,500-8,900	150-470	20	17-28	280	8-9	7-7.5
Point absorber	22-31%	88%	5,500-8,900	150-470	20	17-28	280	8-9	7-7.5

Table 4-21 continued									
Oscillating Wave Surge Converter	22-31%	88%	5,500-8,900	150-470	20	17-28	280	8-9	7-7.5
Oscillating water column	22-31%	88%	5,500-8,900	150-470	20	17-28	280	8-9	7-7.5
Overtopping/ Terminator device	22-31%	88%	5,500-8,900	150-470	20	17-28	280	8-9	7-7.5
Submerged pressure differential	22-31%	88%	5,500-8,900	150-470	20	17-28	280	8-9	7-7.5
Rotating mass	22-31%	88%	5,500-8,900	150-470	20	17-28	280	8-9	7-7.5
Others	22-31%	88%	5,500-8,900	150-470	20	17-28	280	8-9	7-7.5
Horizontal Axis	26-40%	80%	6,700-9,300	130-200	20	17-28	280	10-12	7-7.5
Vertical Axis	26-40%	80%	6,700-9,300	130-200	20	17-28	280	10-12	7-7.5
Oscillating hydrofoil	26-40%	80%	6,700-9,300	130-200	20	17-28	280	10-12	7-7.5
Enclosed tips (venturi)	26-40%	80%	6,700-9,300	130-200	20	17-28	280	10-12	7-7.5
Tidal kite	26-40%	80%	6,700-9,300	130-200	20	17-28	280	10-12	7-7.5

References by criteria:
CF: [255], [287], [288], [289], [290], [291], [292], [3]
REL: [289], [292], [3], [293], [294], [295], [296], [297], [298], [299], [300]
IC: [301], [292], [302]
O&M: [301], [292]
LCoE: [301], [303]
LT: [3], [292]
LCCO$_2$E: [304], [305], [306], [2]
LU: [307], [182]
JC: [308], [309], [310]
PA: [311], [312], [313], [314]

A modified version of the above presented data was created in Table 4-22. Offshore RET were reduced to 4 different types since the attribute values of several alternatives were identical. Hence, monopile, gravity, tripod, jacket and bucket are grouped as fixed offshore RET. The remaining spar-buoy, tension-leg platform (TLP) and semi-submersible are floating offshore RET. All wave RET and all tidal RET are congregated to one group each. For each criterion the highest a_q^{max} (maximum is lightly green colored) and lowest a_q^{min} (minimum is lightly red colored) attribute values were identified, since they are required to build the value functions for each attribute. Thereby, minimization or maximization may be applied.

According to the procedures described above value functions for all 9 criteria are created. For the capacity factor, reliability, lifetime, job creation and public acceptance the preference increases with an increase in the attribute value. Hence, the highest preference (score of 1) is associated to the maximum attribute value of each criterion. For the remaining four criteria (investment cost, operation and maintenance cost, life cycle CO_2 emissions and land use) minimized value functions are applied, since an increase in any of the attribute values leads to a lower preference value (Figure 4-2).

Table 4-22: Modified data set for each attribute by RET

Technology	CF (%)	REL (%)	IC ($/kW$_{el}$)	O&MC ($/kW/a)	LT (years)	LCCO$_2$E (gCO$_2$/kWh$_{el}$)	LU (m^2/kW)	JC (#/MW)	PA (-)
Stoke boiler	90	93	3700	145	20	64	5000	4	5
Fluidized bed boiler	90	96	3700	145	20	64	5000	4	5
Combined heat and power (CHP)	90	78	3700	145	20	78	5000	4	5
Fixed bed gasifiers	90	85	5000	145	20	67	5000	4	5
Fluidized bed gasifiers	90	98	5000	145	20	67	5000	4	5
Entrained flow gasifiers	90	80	5000	145	20	67	5000	4	5
Pyrolysis	88	90	2000	145	20	67	5000	25	5
Anaerobic digestion	91	80	5300	145	20	67	5000	25	5
Thin-film technologies	14	96	4650	43	20	45	78	35	8
Emerging PV	11	96	4650	43	20	55	78	35	8
Multi-junction Cells	23	96	4650	43	20	55	78	35	8
Single-Junction GaAs	18	96	4650	43	20	53	78	35	8
Crystalline Si Cells	16	96	4650	43	20	45	78	35	8
Parabolic Trough	56	92	8000	62	30	23	80	6	8
Horizontal axis lift turbine	35	98	2000	25	20	32	790	13	6.5
Dry Steam power plants	90	96	2500	100	28	38	24	11	5.5
Flash steam power plants	90	96	2900	160	28	59	24	11	5.5
Binary cycle power plants	90	80	4000	153	30	39	24	11	5.5
Run-of-the-river	68	90	2550	50	60	4	440	19	7
Conventional hydroelectric	45	93	2550	50	60	6	440	19	7
Pumped-storage	20	99	2550	50	60	16	440	19	7
Offshore fixed	38	98	3500	130	20	22	790	20	6.5
Offshore floating	44	98	4200	130	20	22	790	20	7.5
Wave	27	88	7200	310	20	23	280	9	7.5
Tidal	33	80	8000	165	20	23	280	11	7.5
Maximum value (a_q^{max})	91	99	8000	310	60	78	5000	35	8
Minimum value (a_q^{min})	11	78	2000	25	20	4	24	4	5

After the value functions are defined the unnormalized weights m_q for each criterion can be assessed. Swing weights are applied, whereas the criterion of the highest importance is the investment cost (IC). A swing from the worst to the best score leads to the greatest satisfaction of the DM. Hence, the investment cost will be set in relation to all other criteria to define the weight of each criterion respectively.

In the specific case, a decrease of IC from $8,000 to $2,000 leads to the highest satisfaction and receives a score of 100. The scale considered in this research ranges from 0-100. Other scales, such as from 0-1, could also be applied. Since the normalization of weights is performed according to Eq. 4-4, any scale can be chosen. Table 4-23 shows the swing weights that are applied in this research (according to the attributes of Table 4-22) along with the final normalized weights w_q. All criteria weights are ordered from highest to lowest.

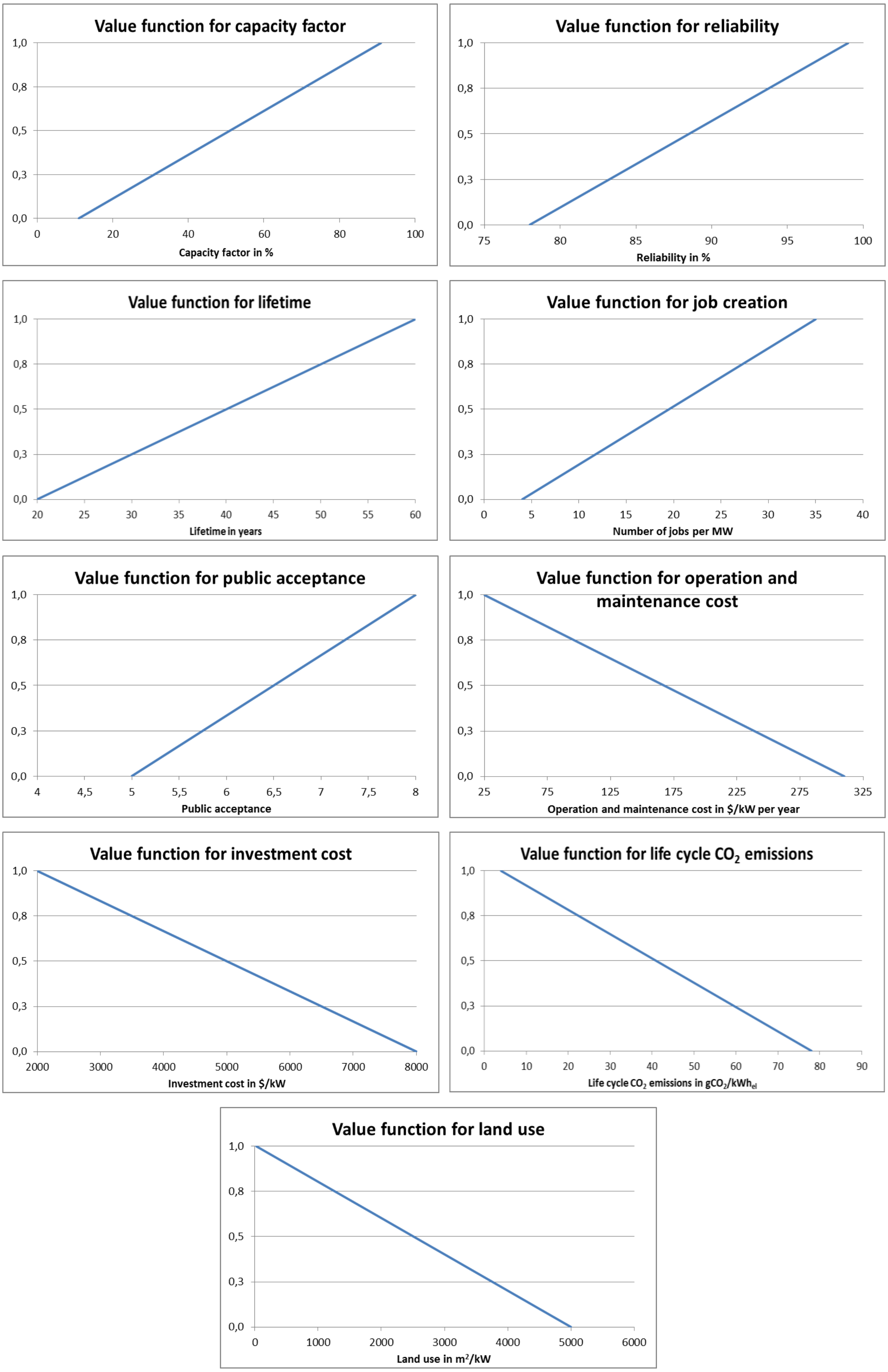


Figure 4-2: Value functions for all attributes

Table 4-23: Swing weights for MCDA

Criteria	Criteria 'Swings'		m_q	w_q
IC ($/kW$_{el}$)	a decrease in IC from 8000-2000 leads to highest satisfaction		100	14.8%
$LCCO_2E$ (gCO_2/kWh_{el})	a decrease in $LCCO_2E$ from 78-4 is equivalent to a IC reduction from	8000-2500	92	13.6%
LU (m^2/kW)	a decrease in LU from 5000-24 is equivalent to a IC reduction from	8000-2800	87	12.8%
PA (-)	an increase in PA from 5-8 is equivalent to a IC reduction from	8000-3000	83	12.3%
O&M ($/kW/a)	a decrease in O&MC from 310-25 is equivalent to a IC reduction from	8000-3400	77	11.4%
JC (#/MW)	an increase in JC from 4-35 is equivalent to a IC reduction from	8000-3500	75	11.1%
CF (%)	an increase in CF from 11-91 is equivalent to a IC reduction from	8000-3800	70	10.4%
REL (%)	an increase in REL from 78-99 is equivalent to a IC reduction from	8000-4000	67	9.9%
LT (years)	an increase in LT from 20-60 is equivalent to a IC reduction from	8000-6500	25	3.7%
Total			675	100.0%

Over time it is expected that the attribute values will change. Since this research analyses the long-term trends, predictions about the attribute value changes are made [292], [315], [316]. For each 10 year period the attribute´s changes over time are assessed. All predictions are summarized in Table D-1 to Table D-8 (p. xvii) of Appendix D – Development trends and expected changes of the alternative´s attribute values over time. Accordingly, the modified data sets are provided in Table D-9, Table D-11 and Table D-13 (p. xxii ff.). From the revised data sets the value functions for each time horizon (10, 20 and 30 years) can be conducted.

For the comparison of RETs over time the normalized weights w_q were redefined for each decade. Thereby, nearly similar weights were assigned to all criteria Table D-10, Table D-12 and Table D-14 (p. xxii ff.). Nonetheless, DMs may change the weights according to the altered attribute ranges that are foreseen over time or simply because DMs expect a higher/lower importance of some criteria (e.g. job creation becomes more important than public acceptance or land use, etc.). The results of the MCDA are presented in Table 4-24. The scores are colored from worst to best, whereas good results are green and bad results a red. Such color scales are applied in various occasions throughout this research to compare alternatives.

The results of the MCDA with the adjusted criteria weights over time lead to the following conclusions:

- Run-of-the-river is the dominating RET over time.
- Hydro and solar PV technologies are the RETs with the highest scores over all time horizons, whereby in the medium to long-term pumped-storage and conventional hydro will be surpassed by most solar PV technologies.

- Onshore wind and floating offshore wind start with a similar score. The lower costs for onshore devices are compensated by better performance, higher acceptance and more jobs created by offshore devices. However, in the following decades the predicted criteria changes seem more favorable for onshore wind if the adequate space is available. Therefore, the score for onshore wind increases slightly, while floating offshore wind devices experience a decreasing trend.

Table 4-24: Results of MCDA

Source	Technology	Current value	10 years	20 years	30 years
Bioenergy	Stoke boiler	0.0549	0.0537	0.0511	0.0470
	Fluidized bed boiler	0.0570	0.0553	0.0527	0.0478
	Combined heat and power (CHP)	0.0406	0.0388	0.0392	0.0365
	Fixed bed gasifiers	0.0438	0.0426	0.0404	0.0354
	Fluidized bed gasifiers	0.0528	0.0503	0.0467	0.0410
	Entrained flow gasifiers	0.0403	0.0403	0.0380	0.0330
	Pyrolysis	0.0690	0.0689	0.0672	0.0653
	Anaerobic digestion	0.0505	0.0492	0.0467	0.0443
Solar	Thin-film technologies	0.1037	0.1118	0.1156	0.1195
	Emerging PV	0.1004	0.1080	0.1121	0.1159
	Multi-junction Cells	0.1027	0.1108	0.1153	0.1196
	Single-Junction GaAs	0.1023	0.1102	0.1145	0.1185
	Crystalline Si Cells	0.1041	0.1124	0.1164	0.1205
	Parabolic Trough	0.0875	0.0913	0.0910	0.0911
Onshore wind	Horizontal axis lift turbine	0.0998	0.1027	0.1056	0.1073
Geothermal	Dry Steam power plants	0.0980	0.0976	0.0966	0.0943
	Flash steam power plants	0.0873	0.0883	0.0862	0.0825
	Binary cycle power plants	0.0782	0.0779	0.0761	0.0718
Hydro	Run-of-the-river	0.1178	0.1200	0.1223	0.1239
	Conventional hydroelectric	0.1149	0.1165	0.1178	0.1194
	Pumped-storage	0.1116	0.1125	0.1130	0.1136
Offshore wind	Offshore fixed	0.0952	0.0975	0.0975	0.0980
	Offshore floating	0.0999	0.1002	0.0992	0.0987
Wave	Wave devices	0.0639	0.0771	0.0856	0.0926
Tidal	Tidal devices	0.0661	0.0746	0.0852	0.0961

- Fixed and floating offshore wind have comparable, decreasing scores, but floating offshore is always superior to fixed offshore, mainly because of the higher acceptance and the slightly higher capacity factor.
- Geothermal power experiences a decrease in scores, whereby the different geothermal RETs perform very diverse; initially all geothermal RETs perform better than wave and tidal, but in the 30 year time frame all geothermal RETs have been overtaken by wave and tidal.
- Bioenergy RETs, except pyrolysis, receive the lowest score across all time horizons. Only in the initial stage pyrolysis performs slightly better than wave and tidal, but then pyrolysis is overtaken within the first decade.
- Wave and tidal experience the greatest improvements over time and might be a reasonable choice for long-term planning; both, wave and tidal are foreseen to become competitive with onshore and offshore wind.

Chapter 4 provides decision support to identify the most appropriate RETs for any given site location. Initially, all RETs are analyzed according to the resource availability and specific site characteristics. If a RET reaches or surpasses the defined requirements for resource availability, then the site characteristics are assessed. Only RETs that meet the essential (exclusive) conditions and the necessary number of conditions will then be considered in the MCDA. The MCDA uses multi-attribute value theory and intends to provide DMs with an overview about the most appropriate RETs for the time series algorithm.

The proposed sequence limits the selection of technologies that are unsuitable for a given location. At the same time, it reflects the DM´s preferences through the criteria weights.

The selection procedure does not imply that only one specific technology will be chosen for the time series algorithm. In contrary, it shall provide DMs with a comprehensive set of RETs that may be used to cover demand. Since the time series algorithm is focused on costs, the precise capacities for each RET still need to be identified. Limits are only imposed for the maximum capacity that may be installed according to the resource availability or spatial limitations. Within the MCDA no consideration was given to the amount of RETs to be installed. While the MCDA provides DMs with a general overview of each RET, further decision analysis may be applied to each scenario so that the actual quantity of each RET can be taken into consideration when choosing a supply alternative.

5. Application of concept to São Miguel – Azores

5.1. General overview of Azores

The Azores are an archipelago of nine distinct and highly diverse islands in the Atlantic Ocean that stretches around 600 km along its northwest-to-southeast axis. Santa Maria is both the most eastern and most southern island in the archipelago and is located around 1,400 km west of the coast of Portugal. All islands vary significantly in size, population, natural resource availability [175], [317], economy as well as heritage and conservation sites, [318], [319], [320] (Table 5-1 and Table 5-2).

Table 5-1: Demographic and energetic overview of Azores islands [32]

	Population (No.)	Households (No.)	Land Area (km^2)	Total Primary Energy (TJ)	Electricity Production (GWh)	Vehicles (No.)
São Miguel	133,281	40,388	745	9,118.09	428.75	56,520
Terceira	55,844	16,922	400	3,102.35	207.66	27,736
Faial	15,527	4,705	173	1,065.11	52.81	8,491
Pico	14,840	4,497	445	701.31	43.55	7,416
São Jorge	9,492	2,876	244	595.84	26.63	5,099
Santa Maria	5,565	1,686	97	453.20	19.89	2,989
Graciosa	4,879	1,466	61	234.15	13.09	2,231
Flores	4,099	1,242	141	271.18	11.37	2,527
Corvo	479	145	17	21.40	1.22	93
Azores	244,006	73,927	2,322	15,562.62	804.76	113,102

Table 5-2: Azores energy resource availability and current RES usage

Fossil fuels	Bioenergy		Onshore wind		Offshore wind		Hydro		Solar		Geothermal		Wave		Tidal	
	R.	U.	R.	U.	R.	U.	R.	U.	R.	U.	R.	U.	R.	U.	R.	U.
São Miguel	✓		✓	☒	✓		✓	☒	✓		✓	☒	✓			
Terceira	✓		✓	☒	✓		✓	☒	✓		✓		✓			
Faial	✓		✓	☒	✓		✓	☒	✓		→		✓		✓	
Pico			✓	☒	✓				✓		→		✓		✓	
São Jorge	✓		✓	☒	✓		✓		✓		→		✓			
Santa Maria			✓	☒	✓				✓				✓			
Graciosa	✓		✓	☒	✓				✓		→		✓			
Flores			✓	☒	✓		✓	☒	✓		→		✓			
Corvo			✓	☒	✓				✓				✓			

Legend/notes:
R. = resource available on particular island and its surrounding ✓
→ = resource available, but with limited potential for contribution
U. = currently used in energy generation portfolio ☒
- Bioenergy potential associated due to agricultural, livestock and diary-related waste products [175]
- Due to the current usage of onshore wind it is expected that offshore wind conditions are also favorable on all islands
- Hydro resource potential has been mostly explored with the exception of São Jorge
- The archipelago presents good solar conditions with small seasonality [321]
- Review of geothermal potential [322]
- The mean wave power potential across northern parts of Azores in the range of 40-75 kW/m [323], [324]
- Tidal potential between Pico and Faial [32]

All of the nine islands already generate parts of their electricity requirements from RES, mainly from wind, hydro or geothermal (Table 5-2). By 2018 75% of the Azores electricity demand and 40% of primary energy are expected to be covered from RES [33], [48]. Based on the ambitious energy targets and the resource availability on the Azores, several projects to increase the share of RES are proposed [80]. In [80] the energy saving potential across all sectors is analyzed and predictions about the amount of electric vehicles on each island are made (Appendix E – Energy data Azores).

Recent development trends and forecasts of demand and generation are summarized in Table 5-3 and Table 5-4. The supply forecast clearly emphasizes the high expectations in geothermal and wind energy in the upcoming years. While some islands (e.g. Graciosa or Faial) will not change noticeably in their energy requirements, others (i.e. São Miguel or Santa Maria) are expected to increase steadily.

Table 5-3: Azores power and energy demand development and trends [10]

	2007	2008	2009	2010	2011	2020
Peak power demand (MW)						
Santa Maria	3	4	4	4	4	5
São Miguel	72	74	74	74	73	72
Terceira	36	36	38	40	36	39
Graciosa	2	2	2	2	2	2
São Jorge	4	5	5	5	5	5
Pico	7	7	8	8	6	9
Faial	9	9	9	9	7	9
Flores	2	2	2	2	2	2
Corvo	0.2	0.3	0.2	0.2	0.2	0.4
Total energy demand (GWh)						
Santa Maria	18	19	19	20	20	25
São Miguel	394	407	407	418	414	425
Terceira	186	193	192	198	195	200
Graciosa	12	13	13	13	13	12
São Jorge	23	25	26	28	28	28
Pico	38	39	40	42	43	48
Faial	45	47	47	48	47	46
Flores	11	11	11	12	11	12
Corvo	1	1	1	1	1	2

Table 5-4: Azores energy generation mix development and trends (GWh) [10]

	2007	2008	2009	2010	2011	2020
Fossil fuels						
Oil	580	605	613	610	587	392
Renewables						
Hydro	31	25	22	31	33	50
Solar				0.02	0.03	0.09
Wind onshore	16	22	31	34	33	83
Wind offshore						
Biomass						53
Geothermal	178	170	162	174	186	289
Other	0.2	0.03	0.1	0.3	0.3	0.4

In order to apply the proposed concepts and methods São Miguel is chosen as study case. Its size, resource availability, generation portfolio and demand development represent an interesting and challenging test bed for energy planning.

5.2. São Miguel

São Miguel, the largest and most populated of the Azores islands, stretches over 750 km^2 and inhabits around 140,000 residents. The population is spread around the whole island, but mainly along the coast. Around 40,000 habitants live in the islands largest city Ponta Delgada. São Miguel's peak load in 2010 was 74.2 MW, whereas 57% of generation was derived from imported fuel-oil [10].

Figure 5-1 highlights the water resources on the island, indicating dozens of small streams and 4 lakes. The national parks of São Miguel are located around the 4 lakes as well as in the central section of the eastern quarter of the island. Owing to its location across three tectonic plates, the island possesses great geothermal resources. Alongside three stratovolcanoes and caldeiras (Sete Cidades, Fogo and Furnas), Geyers and hot springs are spread across the island.

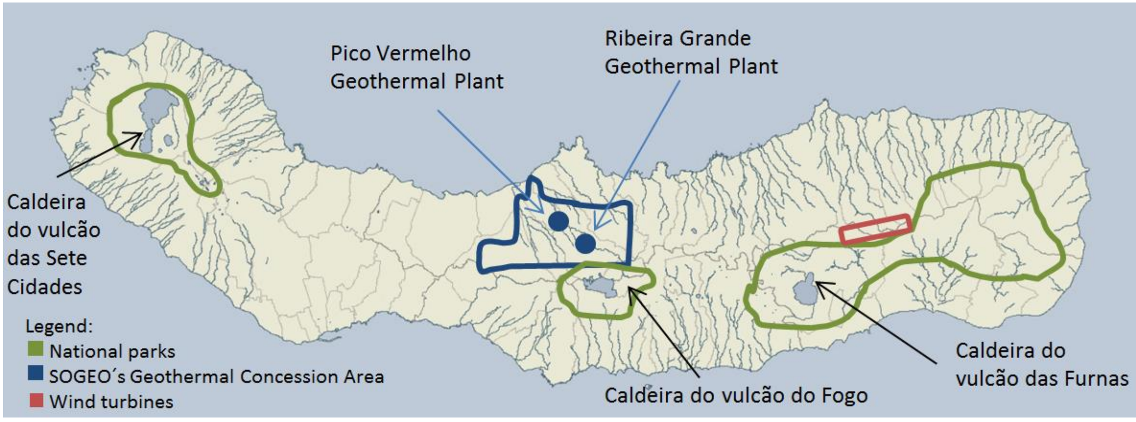


Figure 5-1: Geographic overview of São Miguel (map [325] modified according to [326], [327])

The major economic sectors of São Miguel are (growing) tourism, agriculture, government services and minor commercial activities. Growing energy demand can be associated to tourisms activities, but also a steady increase of population [80].

5.3. Energy breakdown and consumption

In order to predict the future load profiles and to build the scenarios for São Miguel the procedures outlined in Chapter 3.2 are undertaken. Table 5-5 presents the case of São Miguel for Janus RL/JS30. The remaining input/output sheets for São Miguel are listed in Appendix F – Energy consumption and breakdown of São Miguel Island.

Table 5-5: Data input and assumptions for load profile of Janus RL/LS 30 of São Miguel

Input data for the creation of scenarios			Output Janus RL/LS30
General data and assumptions			
Start year	-	2013	2043
Total primary energy	TJ	9,404	5,414
	GWh	2,612	1,504

1

Power unit type	Number of units	Installed capacity (MW)	Approx. full load hours (h/y) *	Capacity factor	Max full load hours (h/y) **	Annual generation (GWh/y) *	Built in	
Fuel - Caldeirão	8	98.06	1,933	22%	3,500	189.57	1987	phase-out
Geoth. - Pico Vermelho	1	13.00	7,675	88%	>8.000	99.78	2006	phase-out
Geoth. - Rib. Grande	1	16.60	4,487	51%	>8.000	74.49	1994	phase-out
Hydro - Tambores	1	0.09	1,606	18%	>4.000	0.15	1909	phase-out
Hydro - Fábrica Nova	1	0.61	285	3%	>4.000	0.17	1927	phase-out
Hydro - Canário	1	0.40	6,303	72%	>4.000	2.52	1991	in range
Hydro - Foz da Ribeira	1	0.80	5,918	68%	>4.000	4.73	1990	in range
Hydro - Ribeira da Praia	1	0.80	4,660	53%	>4.000	3.73	1991	in range
Hydro - Salto do Cabrito	1	0.67	6,804	78%	>4.000	4.56	2006	in range
Hydro - Túneis	1	1.66	6,381	73%	>4.000	10.58	1951	phase-out
Other (Biogas and PV)	1	0.12	3,700	42%	N/A	0.44	2010	phase-out
Wind - Graminhais	10	9.00	2,384	27%	2,500	21.46	2012	phase-out
Total		141.81				412.18		

2

Electricity consumption		GWh	412.18	535.84
Share of electricity on total primary energy demand		%	15.78	35.63
Total installed capacity		MW	141.81	
Available installed RES capacity for electricity generation		MW	26.45	
Available installed fossil fuel capacity for electricity generation		MW	32.69	
Annual energy demand	increase	%/y	-	
	decrease	%/y	0.5	
Annual electricity demand	increase	%/y	1.0	
	decrease	%/y	-	

4

	current		in 30 years		Saving potential by sector
Breakdown final energy consumption by sector	GWh/y *	% *	GWh/y *	% *	
Residential		32.6%		35.0%	54%
Commercial		45.4%		45.0%	33%
Industry		21.7%		17.0%	0%
Transportation		0.3%		3.0%	22%
Projected electricity consumption after applying saving potential			GWh/y		351.46

5

Total electricity generation to be covered from RES	GWh/y	346.27
Electricity generation required from new RES in 30 years	GWh/y	330.73
Fossil fuel based in 30 years	GWh/y	5.19
Maximum electricity available from fossil fuel units	GWh/y	114.41
Peak power demand over the year	MW	59.65
Available peak power: fossil fuel capacity + baseload RES * capacity factor	MW	46.63

* Requires the information of either approx. full load hours or annual generation or percentage or annual demand
** shall determine the upper bound of full load hours under which the fossil fuel units can be operated

Table 5-5 provides all information relevant to the current power plant portfolio [328], [329], [330]. A breakdown of final energy consumption by sector is applied according to [331]. While an increase of electricity demand is expected over the years, a minor reduction of the annual energy demand is foreseen. The reduced primary energy demand can be explained with the increasing share of electricity from RES as well as the higher efficiency of electrical appliances at the end-user level. Losses due to the low conversion efficiency of fossil fuels – on São Miguel the generators operate at 43% efficiency [332] – can be omitted. By applying the anticipated electricity saving potential (Table 3-3 p. 41) the expected consumption in 30 years can be identified.

The electricity demand profile of São Miguel (2010) is illustrated in Figure 5-2 and will be used to conduct the future profiles for each of the 18 scenarios of the island (p. 126 ff.).

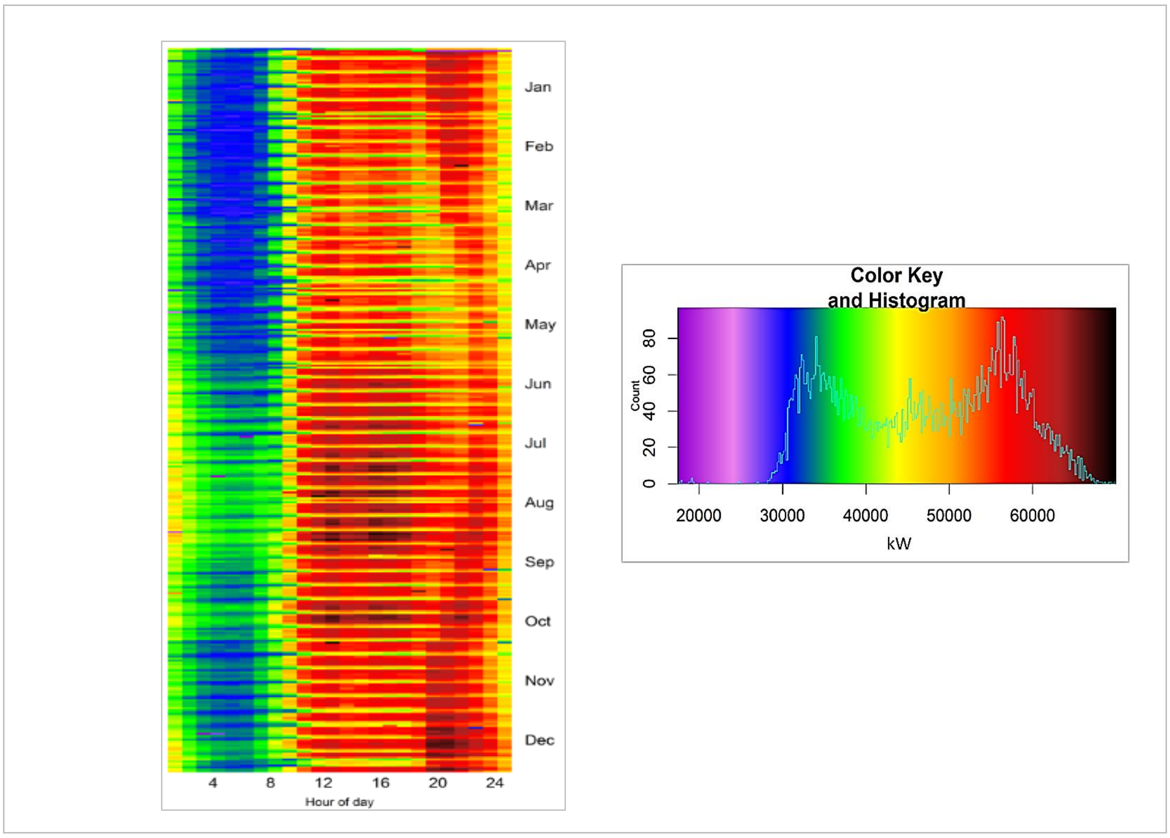


Figure 5-2: Electricity demand profile and histogram of São Miguel (2010)

The demand profile clearly illustrates the timely distribution of consumption on São Miguel (see also histogram for count of occurrence). There is a clear night/morning (off-peak: 12am to 8am) low of approximately 30-35 MW for most of the year. Only during the summer season demand in these hours is slightly higher with around 40 MW. Between 8-9am there is a sudden demand increase, which can be mainly associated to the start of working hours. Here especially the commercial sector (administration and tourism) has a major influence. From June until late October there is a significant peak of 55-65 MW between 10am and 5pm. Another peak period can be observed during late evening hours. However, the time of the second peak changes over the year. During the winter months the peak usually occurs between 6pm and 9pm, whereas during the summer period there is a shift of late evening consumption by around 2 hours (usually occurs between 8pm and 11pm). Apart from the summer or main season (June to October) the late evening peak is often higher than the peak during the day, but mainly in the range of 55-65 MW.

Because of the distinct consumption behavior that could be identified with the current electricity demand profile, an adjustment of the load shifting procedures is proposed. The currently suggested load shifting would cause a further increase of peak demand between 8pm and midnight. Table 5-6 lists the adjusted, even stricter and more demanding, rules to conduct all load profiles comprising LS.

By means of demand forecasting models more precise load shifts could be performed [333], [334], [335]. This could particularly focus on the different shifting requirements between summer and winter, but also for the early morning hours (4-7am). Since São Miguel bears great potential for the use of geothermal energy (a base load RES), ideally the load should be flattened to have a constantly high base load.

Table 5-6: Adjusted load shifting considerations for São Miguel

Sector	Service of load shift	Load shifting considerations
Residential	Wet appliances	Rule: 80% of wet appliances will be shifted from the period 12pm-12am to 12am-6am, whereas each 2 hours during peak demand will be shifted to 1 hour during off-peak; e.g. hours 12pm and 1pm are shifted to hour 12am. The usage of wet appliances between 6am and 12pm is not considered in the load shifting.
Residential and commercial	Space/water heating and cooling	Rule 1: 5% of space and water heating as well as 10% of space cooling occurring during peak hours (8am-4pm) will be shifted two hours prior to its current actual usage, so that the overall peak can be smoothened and the morning off-peak (6am-8am) can already cover some demand. Rule 2: 5% of space and water heating will be shifted from 6pm and 7pm to 5pm.
Transport	Electric vehicles	Rule: Transport electricity consumption will be moved from 12pm-12am to 12am-6am, whereas demand from each two hour interval is shifted to one hour during off-peak. For representative purposes the hours 12pm to 2pm will be shifted to 12am of the following day. Consumption occurring between 6am and 12pm and will remain unchanged.

After applying the procedures outlined in Chapter 3.2 the load profiles for all scenarios can be obtained. Janus 30RL and Janus 30LS are illustrated in Figure 5-3 and Figure 5-4, whereas the major difference between scenarios with a regular load and ones with load shifting are demonstrated. Especially the histogram in Figure 5-4 highlights the more balanced occurrence of loads throughout the year; i.e. peaks can be shaved and valleys can be lifted.

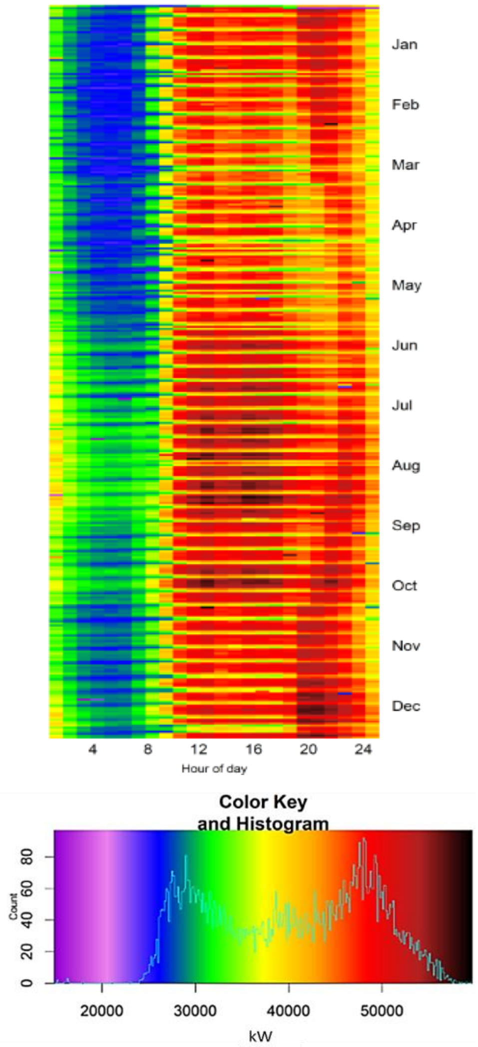


Figure 5-3: Load profile São Miguel Janus 30RL

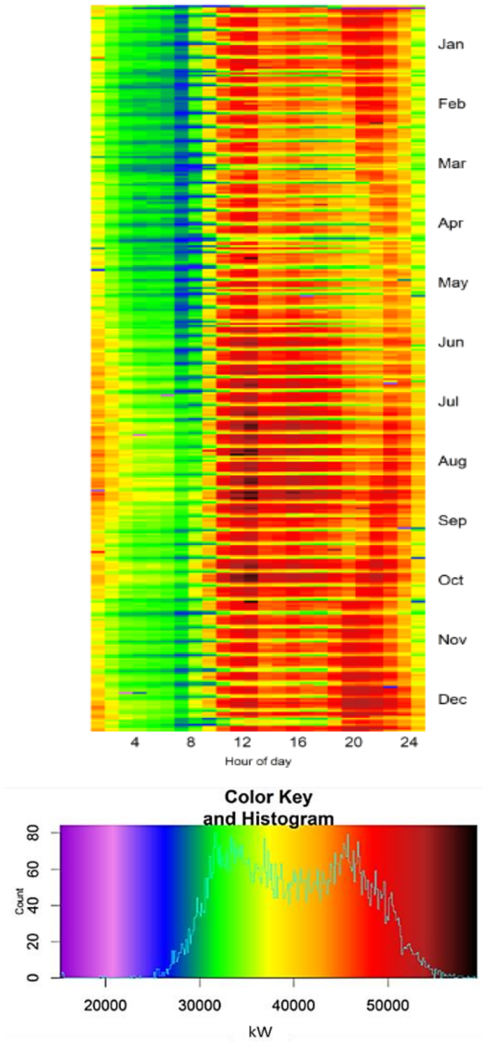


Figure 5-4: Load profile São Miguel Janus 30LS

The comparison of histograms for all scenarios and time frames shows the drastic changes in demand occurrence (Figure 5-5 and Figure 5-6). The annual load profiles that belong to each histogram are listed in Appendix G – Load profiles for São Miguel scenarios (p. xxxv ff.). By applying the same color key scale (range 20,000-120,000 MW), the changes across the scenarios are presented. The histograms for Janus and Aurora are identical since the same procedures and assumptions are undertaken to build the load profiles. In Janus and Aurora the changes over time are small. Between Janus/Aurora 10 and Janus/Aurora 20 there is an increase in consumption. However, in the next 10 years a slightly steeper decrease is expected so that demand in Janus/Aurora 30 is foreseen to be lower than in Janus/Aurora 10. Also, the more balanced demand occurrence in scenarios comprising load shifting can be noticed.[34]

[34] The histograms in Figure 5-3 and Figure 5-4 differ from the ones shown in Figure 5-5. This is because of the different color key scales that are used for both cases. Also, the count in Figure 5-3 and Figure 5-4 is more precise, for which reason the count for each demand occurred is lower.

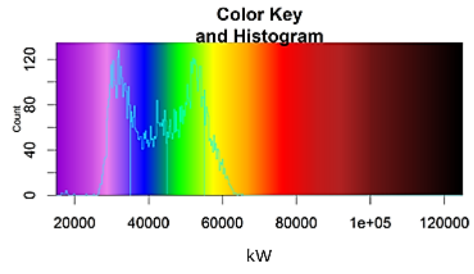
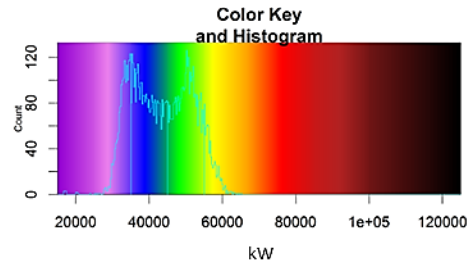
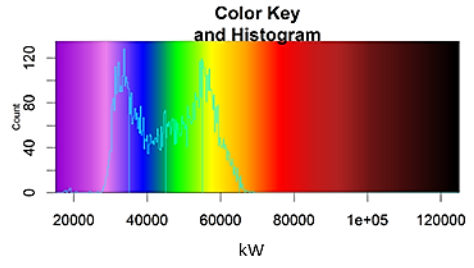
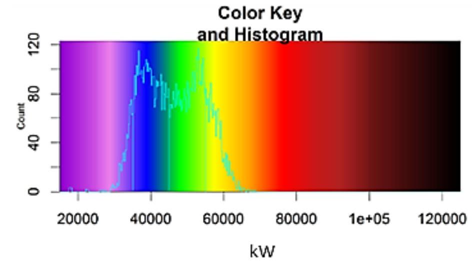
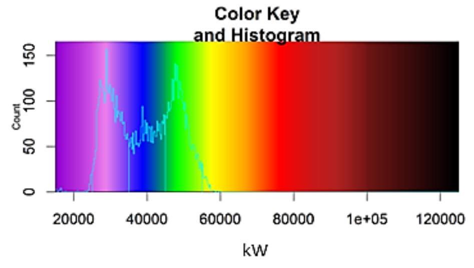
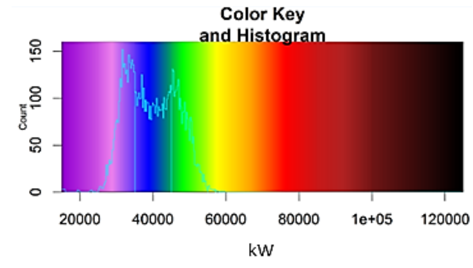
	Regular load	Load shifting
Janus and Aurora 10		
Janus and Aurora 20		
Janus and Aurora 30		

Figure 5-5: Histograms for scenarios of Janus and Aurora

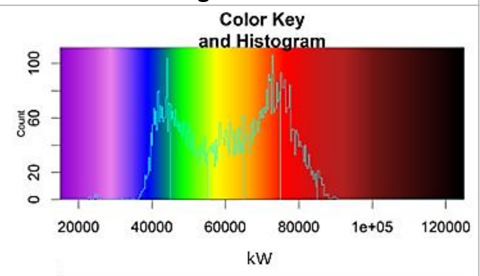
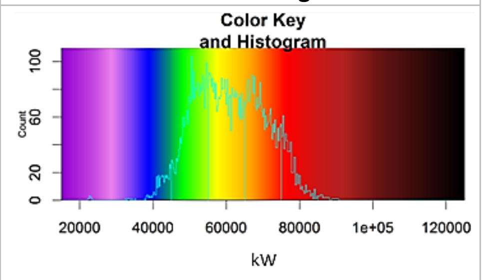
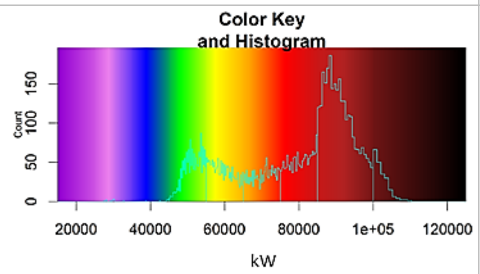
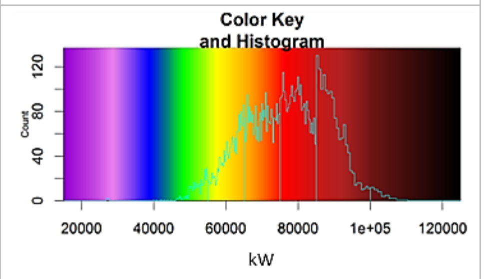
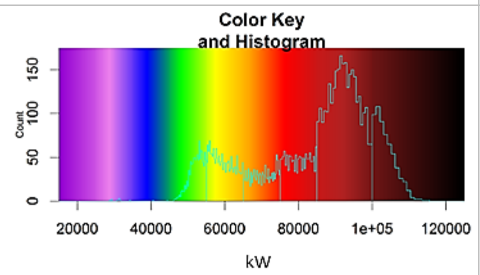
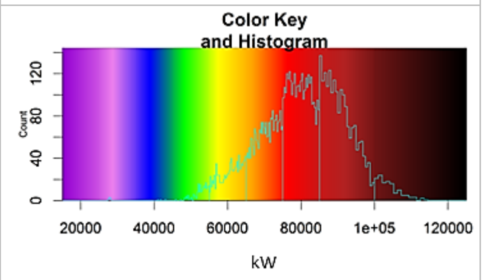
	Regular load	Load shifting
Antevorta 10		
Antevorta 20		
Antevorta 30		

Figure 5-6: Histograms for scenarios of Antevorta

In the case of Antevorta (Figure 5-6) the changes are even more recognizable. On the one hand, electricity demand is increasing considerably over time as a result of vector shifting. The most significant changes occur from Antevorta 10 to Antevorta 20 on the regular load (left side Figure 5-6), where a significant demand occurrence in the range of 55-75 MW moves to around 85 MW. This substantial increase can be explained with the fact that load increases due to vector shifts are expected in the same timely proportion as the initial electricity profile, i.e. vector shifts increase the actual peaks.

On the other hand, the load shifting potential can be highlighted (right side Figure 5-6): major demand portions can be shifted, valleys for each time horizon can be filled and peaks can be reduced. All undertaken load shifting procedures are considered in the illustration of the load profiles and histograms.

5.4. Resource availability and local characteristics

After analyzing the demand and its expected development over the years, now the supply side is examined. Therefore, the resource availability and local characteristics of São Miguel are assessed to pre-select locally suitable RETs for further evaluation.

The analysis starts with bioenergy. For more precise descriptions about each condition and how to associate the respective values to each condition it is referred to Chapter 4.1 (p. 81 ff.). Little biomass feedstock is expected on São Miguel, whereas only food and animal waste might be available in limited quantities. It is not foreseen to grow specific energy crops or make use of woody biomass. Therefore, the biomass RET choices are constrained and only anaerobic digestion is considered for further study (Table 5-7).

Due to its expected small contribution to generation, anaerobic digesters (if selected for further study) are considered as backup generators. The capability to store gas, allows a conversion to electricity when needed. For that reason, anaerobic digestion represents a valuable alternative to reduce the required storage capacity and storage size.

Table 5-7: Bioenergy technology pre-selection for São Miguel

Condition		Resource availability and site characteristics		Stoke boiler	Fluidized bed boiler	Combined heat and power	Fixed bed gasifier	Fluidized bed gasifier	Entrained flow gasifier	Pyrolysis	Anaerobic digestion
A.	Type of biomass feedstock available	insert 1 or 0	0	0	0	0	0	0	0	0	0
		insert 2 or 0	0	0	0	0	0	0	0	0	0
		insert 3 or 0	0	0	0	0	0	0	0	0	0
		insert 4 or 0	0	0	0	0	0	0	0	0	0
		insert 5 or 0	5	0	1	0	0	0	0	0	1
		insert 6 or 0	6	0	0	0	0	0	1	1	1
		insert 7 or 0	0	0	0	0	0	0	0	0	0
B.	Feedstock vs. food	insert 1, 2 or 3	1	0	0	0	0	0	0	0	1
C.	Land space availability to grow or retrieve feedstock	insert 1, 2 or 3	1	0	0	0	0	0	0	0	1
D.	Seasonal feedstock availability	insert 1, 2 or 3	3	0	1	0	0	0	1	0	0
E.	Particle size requirements	insert 0<value<100	100	0	0	0	0	0	0	0	1
F.	Moisture content requirements (wet basis)	insert 0<value<100	40	0	1	0	0	0	0	0	0
			70	0	0	0	0	0	0	0	1
G.	Purpose	insert 1 or 0	1	0	1	0	0	0	1	0	0
		insert 2 or 0	0	0	0	0	0	0	0	0	0
		insert 3 or 0	0	0	0	0	0	0	0	0	0
		insert 4 or 0	4	0	0	0	0	0	0	0	1
	Total			**0**	**4**	**0**	**0**	**0**	**3**	**1**	**5**

The annual solar radiation on São Miguel is around 1,800 kWh/m^2 [336]. However, the Azores are known for its unstable and highly variable weather. Clouds occur most of the time; during summer time around 50-60% of daylight hours and during winter time even up to 75% of daylight hours [337]. This has considerable influences on the selection of the PV system, since it is required to work under indirect sunlight. Depending on the development status and performance, thin-film technologies or monocrystalline cells are suggested (Table 5-8).

Hourly data of the solar irradiance for Ponta Delgada is gathered (Figure 5-7) [338]. It shows the timely distribution over the year. The highest irradiance can be obtained during the summer months. This represents a great opportunity to cover cooling requirements, which are expected to be high during these months. Generally, solar energy represents a daily source for electricity generation. Its higher predictability makes it a more reliable variable RES than wind. This can be of great interest when planning towards 100% RES, since the storage system is less likely to be discharged over several days or weeks if only a storage system along with a large PV system were to be installed.

Table 5-8: Solar energy technology pre-selection for São Miguel

Condition		Resource availability and site characteristics		Thin-film technologies						Crystalline si-cells		
				Amorphous Si	CdTe	CIS/CIGS	Emerging PV	Multi-junction cells	Single-junction cells	Mono-crystalline	Poly-crystalline	Parabolic trough
A.	Solar radiation	insert 0<value<2700	1800	1	1	1	1	1	1	1	1	1
B.	Shading	insert 1, 2 or 3	2	1	1	1	0	0	0	0	0	0
C.	Space/rooftop availability vs PV system size	insert 1, 2 or 3	1	1	1	1	1	1	1	1	1	1
D.	Temperature influence	insert 1, 2 or 3	2	1	1	1	1	0	1	1	0	0
E.	Development status	insert 1, 2 or 3	3	0	0	0	0	0	0	1	1	0
	Total			**4**	**4**	**4**	**3**	**2**	**3**	**4**	**3**	**2**

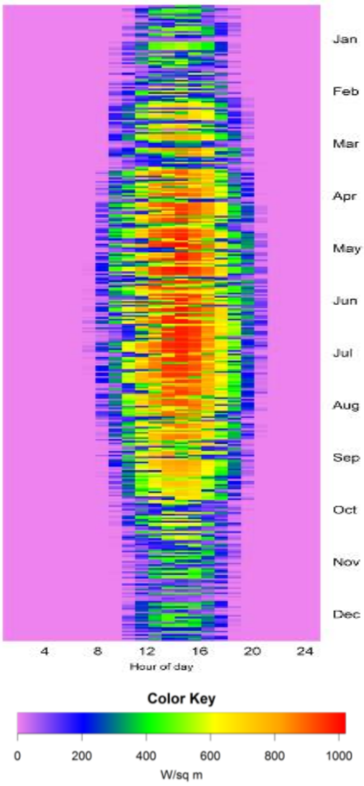


Figure 5-7: Solar irradiance Ponta Delgada

The wind conditions on São Miguel seem favorable which can be recognized by the installation of ten 0.9 MW wind turbines in 2012. All conditions in the pre-selection procedure are met (Table 5-9) and the annual timely occurrence of the wind speed is illustrated in Figure 5-8 [338].

Table 5-9: Wind energy technology pre-selection for São Miguel

Condition		Resource availability and site characteristics		Wind turbine
A.	Wind speed	insert 0.0<value<30.0	7.8	1
B.	Wind occurrence	insert 1, 2 or 3	2	1
C.	Land accessibility	insert 1, 2 or 3	2	1
D.	Protected sites	insert 1, 2 yes, 2 no or 3	2 yes	1
	Total			**4**

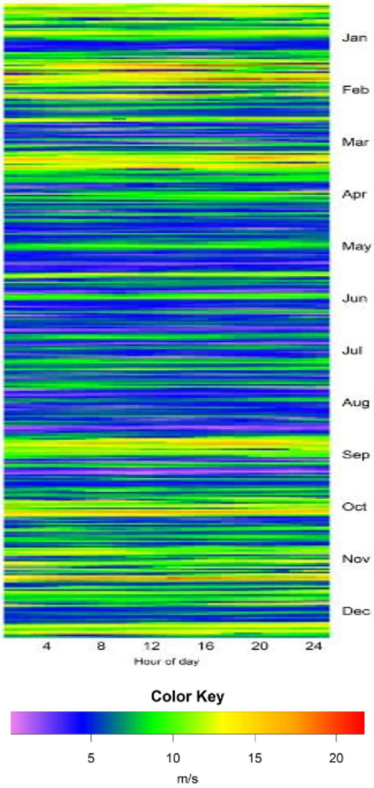


Figure 5-8: Wind speed over the year

Conversely, there is one major drawback in using wind. High wind speeds mainly occur during winter, when demand is low. Throughout the summer season the wind speed remains low or close to zero for longer periods. In such cases a storage unit must be capable to discharge for several days (or even weeks) without substantially recharging itself from wind.

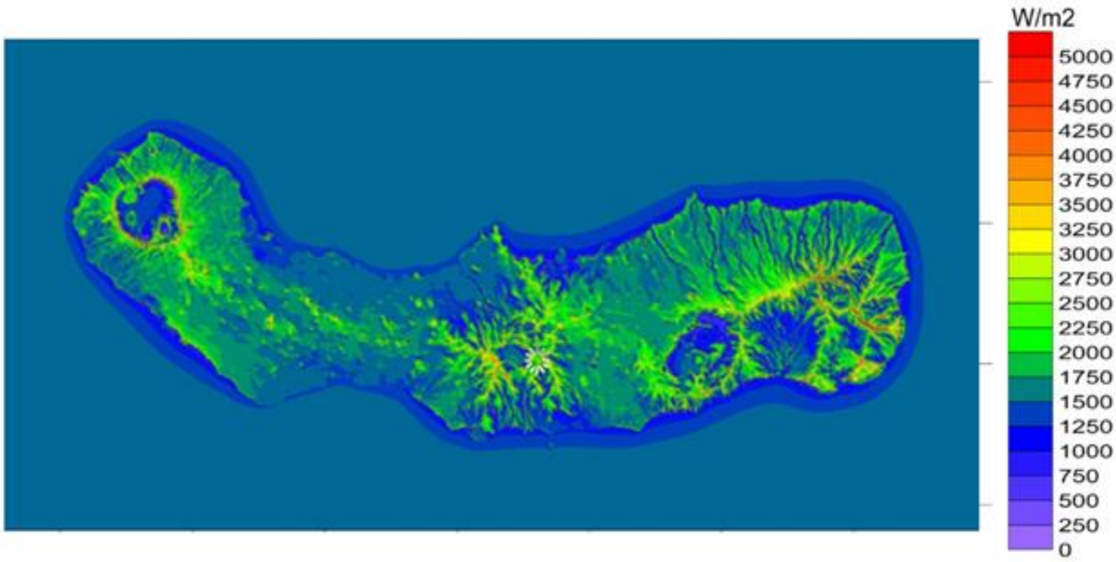


Figure 5-9: Power density (W/m^2) for São Miguel island at 10 m above ground level [339]

In addition to the already installed wind turbines, the greatest potential for further installations is given in the eastern parts of the island as well as around the 4 major lakes (Furnas, Fogo, Azul and Verde) (Figure 5-9).

Geothermal energy already largely contributes to São Miguel´s electricity portfolio. Due to the intersection of three tectonic plates (geologic triple junction) São Miguel possesses a high geothermal gradient that leads to the desired heat medium temperature at reasonable depths. The permeable formations in Ribeira Grande range from 700 to 1,300 m (applied in Table 5-10) and in Pico Vermelho from 450-900 m [340]. By means of São Miguel's required power rating only binary cycle power plants are considered for further analysis.

Table 5-10: Geothermal energy technology pre-selection for São Miguel

Condition		Resource availability and site characteristics		Dry steam power plant	Flash steam power plant	Binary cycle power plant
A.	Geothermal gradient	insert value (e.g. 2.3)		15-30		
B.	Resource depth*	insert 1,200<value<3,000		700-1,300		
C.	Average ground temperature	insert value (e.g. 10.0)		15.7		
D.	Actual temperature at desired depth			245		
E.	Required heat medium temperature			1	1	1
F.	Heat medium and working fluid	insert 1 or 0	0	1	0	0
		insert 2 or 0	0	0	1	0
		insert 3 or 0	3	0	0	1
G.	Power ratings	insert 0,0<value<100	2	0	0	1
	Total			**2**	**2**	**3**

* The resource depth may be lower than the indicated value (see Pico Vermelho formation on São Miguel).

The daily contribution of geothermal power in 2010 is shown in Figure 5-10 [341]. A step-wise increase in power generation can be noticed, since the power plants capacity was uprated twice in 2010. Further plans to increase the contribution of geothermal power already exist, either by adding to the Pico Vermelho plant or by building a new plant on the island [82].

Hydro energy is another RES that is already used on São Miguel. Various streams around the island, with different head heights and flow volumes, provide an opportunity for the use of hydro energy. The island also possesses possibilities for pumped-storage, whereas the natural lakes or even artificial reservoirs could be considered (Table 5-11).

Currently, there are 7 hydro plants with a total capacity of 5 MW installed. Over the year the plants operate over a range of 0-3 MW; the majority of time at around 2.5 MW (Figure 5-11) [341]. According to the current operation pattern the hydro units run as base load. Yet, there is potential to increase operation at Foz da Ribeira, Nova, Ribeira da Praia and Tuneis. All these units run at less than half of their rated power in 2010.

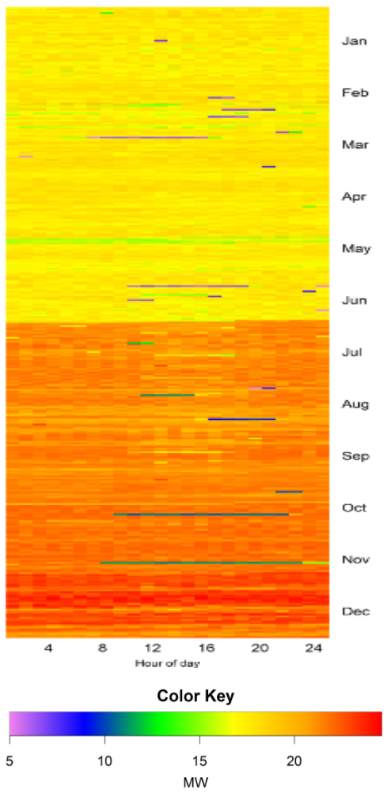


Figure 5-10: Geothermal power generation over the year

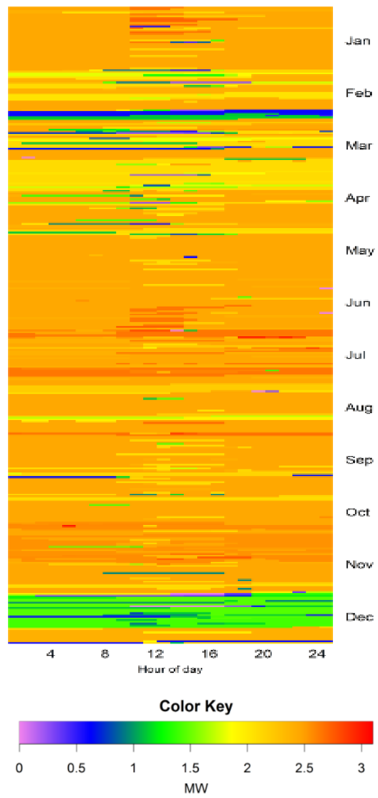


Figure 5-11: Hydro power generation over the year

Table 5-11: Hydro energy technology pre-selection for São Miguel

Condition		Scoring/Comments	Resource availability and site characteristics		Run-of-the-river	Conventional hydroelectric	Pumped-storage
A.	Water resource	Running river streams = 1;	insert 1 or 0	1	1	0	1
		running rivers with potential for dams = 2;	insert 2 or 0	2	0	1	0
		lakes = 3;	insert 3 or 0	3	0	0	1
		sea = 4	insert 4 or 0	4	0	0	1
B.	Storage possibility	No storage = 1;	insert 1 or 0	0	N/A	N/A	0
		artificial storage = 2;	insert 2 or 0	2			1
		natural storage reservoir= 3	insert 3 or 0	3			1
C.	Seasonality	Low = 1; medium = 2; high = 3	insert 1, 2 or 3	2	0	1	1
D.	Head height	Pelton	insert 0<value<1300		-	-	1
		Cross-flow		min	1	1	0
		Bulb-turbine		20	1	1	-
		Straflo		max	0	0	-
		Kaplan		200	1	1	-
		Francis			-	-	1
E.	Flow volume	Pelton	insert 0<value<1000	50	-	-	1
		Cross-flow			1	1	1
		Bulb-turbine			1	1	-
		Straflo			1	1	-
		Kaplan			1	1	-
		Francis			-	-	0
	Summary	Pelton	**Summarizes all conditions and characteristics to determine the power plants and turbine type**		-	-	**1**
		Cross-flow			**1**	**1**	**0**
		Bulb-turbine			**1**	**1**	-
		Straflo			**0**	**0**	-
		Kaplan			**1**	**1**	-
		Francis			-	-	**0**

The assessment of offshore RES and their local characteristics represents an even greater challenge than for onshore RES. Tidal currents around most Azores islands are very low and have not been subject to many studies yet. Only between Pico and Faial velocities of up to 0.6 m/s were found [342]. Due to the limited tidal current resource, tidal RETs are not considered for further study on São Miguel.

Offshore wind conditions are foreseen to follow the pattern of onshore wind (Figure 5-8 p. 130). Only a minor increase of the annual wind speed mean from 7.8 m/s to 8.0 m/s is considered. For the mean wave power it may be referred to [323] and [324], whereas 50 kW/m wave crest length are assumed in the pre-selection model. The wave time series is based on measures of the National Data Buoy Center [343]. The water depth around the island falls fast beyond 100 m [342]. Moderate scores were associated for all remaining site characteristics so that the model could be completed. The results (Table 5-12) indicate that mainly because of the water depth, only a few offshore RETs seem favorable on São Miguel. Only floating offshore wind and selected wave devices are considered for further study.

While it was initially planned to explore the role offshore RETs might have in the future energy supply, the pre-selection process already limited the number of suitable offshore RETs considerably. In general, the approach for the consideration of these technologies is similar to other technologies. Yet, it is a major challenge to identify one offshore concept that performs well under diverse resource availability and site characteristics. In the case of fixed offshore wind, the first steps are made as more and more projects are being realized, but for floating offshore wind, wave and tidal devices there is still a challenging road ahead until full-scale devices will be installed in large numbers.

Table 5-12: Offshore energy technology pre-selection for São Miguel

	Technology classification for Offshore Technologies	Offshore Resource Availability: Wind speed at 90m [m/s]	Offshore Resource Availability: Mean wave power [kW/m]	Offshore Resource Availability: Tidal stream velocity [m/s]	Further selection process	Site Characteristics: a. water depth	b. sea roughness	c. extreme weather conditions	d. gravity/ inertia	e. aero-dynamics	f. hydro-dynamics	g. elasticity	h. soil conditions and seabed stability	i. mooring dynamics	j. construction	k. operation and maintenance	l. access to construction site	m. ship and ice impact	n. current/wave direction	suggested technology
		8	50	0.06		100	2	2	2	2	2	1	2	1	1	2	1	3	2	
Offshore Wind Devices	Monopile					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Gravity					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tripod	1			yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Jacket/Lattice					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Bucket					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Spar-buoy					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	TLP	1			yes	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
	Semi-Submersible					1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Wave Energy Devices	Attenuator		1		yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Point absorber		1		yes	1	1	1	1	1	1	1	0	1	1	1	1	1	1	13
	Oscillating Wave Surge Converter		0		no	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Oscillating water		1		yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Overtopping/Terminator device		1		yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Submerged pressure differential		1		yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Rotating mass		1		yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Others		1		yes	1	1	1	0	1	1	1	1	1	1	1	1	1	1	13
Tidal Energy Devices	Horizontal Axis			0	no	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Vertical Axis			0	no	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Oscillating hydrofoil			0	no	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Enclosed tips (venturi)			0	no	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tidal kite			0	no	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

5.5. Selection of renewable energy technology choices for São Miguel

The pre-selection of RETs based on local resource availability and site characteristics already reduced the number of RETs greatly. For the actual MCDA based on sustainability criteria the data sets from Chapter 4.2.2 (p. 111 ff.) are used. Swing weights are applied and the analysis is performed for each time horizon bearing in the mind the development trends of all attributes.

While hydro energy is preferred as base load RES, solar energy is the favored variable RES. Both RES remain dominant in their load category over the analyzed time horizons. However, due to its substantial resource availability geothermal energy must also be considered as major base load RES in São Miguel´s energy system. Offshore technologies are expected to compete with mainly onshore wind in the medium to long-term (Table 5-13). The applied color scale ranges from red (worst) to green (best).

Table 5-13: Results of MCDA for São Miguel

Source	Technology	Current value	10 years	20 years	30 years
Bioenergy	Anaerobic digestion	0.0505	0.0492	0.0467	0.0443
Solar	Thin-film technologies	0.1037	0.1118	0.1156	0.1195
	Crystalline Si Cells	0.1041	0.1124	0.1164	0.1205
Onshore wind	Horizontal axis lift turbine	0.0998	0.1027	0.1056	0.1073
Geothermal	Binary cycle power plants	0.0782	0.0779	0.0761	0.0718
Hydro	Run-of-the-river	0.1178	0.1200	0.1223	0.1239
	Conventional hydroelectric	0.1149	0.1165	0.1178	0.1194
	Pumped-storage	0.1116	0.1125	0.1130	0.1136
Offshore wind	Offshore floating	0.0999	0.1002	0.0992	0.0987
Wave	Wave devices	0.0639	0.0771	0.0856	0.0926

In order to perform the time series algorithm limits for the availability of each RES are implemented. This is particularly important for the selection of base load technologies, since they should cover the predicted base load requirements. A deficit in base load capacities causes increased demand for variable RES as well as energy storage. It is expected that the capacity of hydro power cannot be more than doubled with the available streams on the island. Therefore, the additional availability of hydro power is set to 5 MW. For geothermal power there is no limitation, since the resource availability is considerably larger than São Miguel's total energy requirements. In the case of bioenergy, it is foreseen that contributions remain very limited; with a maximum of 1 MW over the time horizons. Variable RES can also be limited in their capacities. This seems especially the case for solar energy. The contribution from solar energy is expected to be lower than 30 MW, which already requires the size of around 288,000 m^2 or 40 soccer fields.[35]

[35] A soccer field is typically in the range of 100-110 m long and 64-75 m wide. Hence, the area is between 6,400-8250 m^2. Considering the required solar panel area of 288,000 m^2 this would represent between 35-45 soccer fields.

For wind, both onshore and offshore, as well as for wave energy no constraints are imposed. There is sufficient space on and around the island to install further wind turbines and wave devices.

5.6. Results of time series algorithm

The last part of Chapter 5 presents the results of the time series algorithm for the case of São Miguel. A total of 18 scenarios were assessed and the combinations of RETs with respect to the overall system cost were analyzed. Since the objective was to identify future supply alternatives 100% RES based, the initial analysis focusses on the results of Aurora and Antevorta. In Janus there are still fossil fuel units running in all time horizons. The effects of small contributions (up to 5% in Aurora and Antevorta) of fossil fuels are then compared with the results of Janus, where shares of 10-30% are still generated from thermal units. For both cases selected solutions are presented, whereas the key components of the supply system are debated. Finally, a sensitivity analysis for the contribution of base load RES is conducted.

5.6.1. Supply alternatives based on 100% RES

In the case of São Miguel the current energy portfolio already includes a significant share of RES. Over the upcoming decades it is expected to further increase the contribution, so that over three-fourth of the energy demand can be covered from RES. With the ambition to even surpass the set targets, supply alternatives for 100% RES supply were conducted. Since the scenarios of Janus only intend to cover the additional energy demand over the decades as well as the energy demand that results from the phase-out of fossil fuel units, but over the decades some of these thermal units will still remain active, none of the Janus scenarios achieves 100% RES supply. Hence, the first scenario evaluation focusses on Aurora and Antevorta, where an immediate change to RES (Aurora & Antevorta) plus additional energy demand due to vector shifts (only Antevorta) are analyzed.

Figure 5-12 gives an overview of the total system cost for the 12 scenarios (six per decade and six per load profile type) in relation to the fossil fuel generation cost of $100 (grey lines) and $150 (colorful lines) per MWh. All costs are inflated to the start year of the considered time horizon. The differences of solutions are evidently visible. None of the solutions comes close to the actual generation cost of a system that would be entirely based on thermal generators. The best solutions are achieved in the long-term, for a profile with load shifts (LS) and for combinations of several variable RES. Yet, the best solution (combination of selected base load RES with solar, onshore and offshore wind) is 23% more expensive than a fossil fuel system.

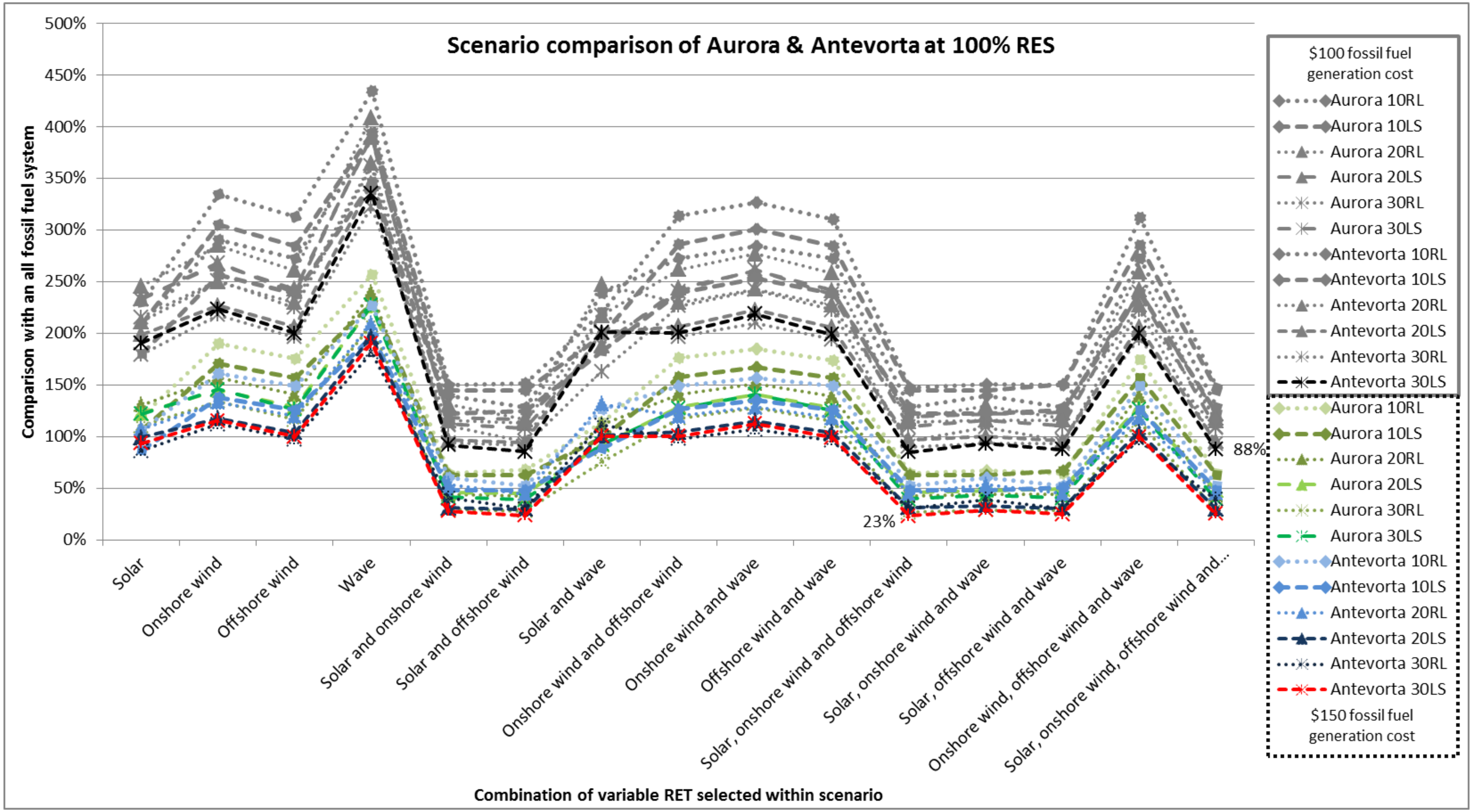


Figure 5-12: Cost comparison for scenarios of Aurora and Antevorta at 100% RES

Henceforth, more precise information about technical features of the best 100% RES solution is provided. This includes the RES capacities, the storage parameters, energy spillage and the actual demand-supply profile. For Antevorta 30LS the base load technologies that lead to the least cost are geothermal and hydro. 2.67 MW of hydro is still in operation. An additional 0.66 MW of hydro shall be added to the system along with 60.35 MW of geothermal power. This adds up to almost 64 MW, which presents the capacity that is exceeded in around 90% of the hours of the year. Hence, the base load maximum can be defined according to the load duration curve (Figure 5-13). Yet, modification of the base load contribution need to be performed, since initial trials of a modified base load limit (i.e. up to 70% of hours of year) led to the expectation that lower overall system costs can be achieved (see Chapter 5.6.3 p. 154).

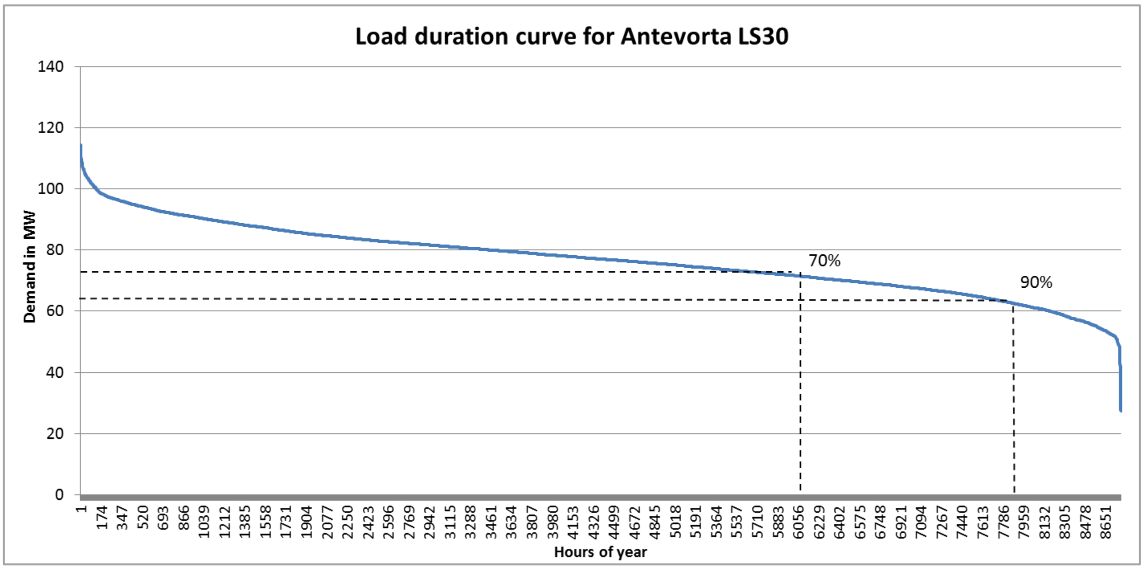


Figure 5-13: Load duration curve for Antevorta LS30

After defining the base load capacities the capacities of the variable RETs were assessed. In order to meet the demand equation of the time series algorithm at the lowest overall system cost the following RET capacities were identified according to the formulations in Chapter 3.3: 29.82 MW solar, 2.62 MW onshore wind and 44.47 MW offshore wind. The maximum capacity of solar was limited to 30 MW (see Chapter 5.5). For the wind resources no limits were imposed.

Taking into consideration the resource availabilities of all selected RES, the time series could be conducted and the storage parameters could be identified accordingly. For the specific case the modified storage power is rated with 46.72 MW and the storage energy size with 16.909 MWh. This presents a massive storage unit, which on a small island system might be very difficult to realize. Only with pumped hydro and by using the natural lakes as reservoir such a storage system may be installed on São Miguel.

Looking at the demand-supply profiles over the months the reason for the large energy size of the storage system becomes obvious. While there is a regular interaction between RES and the storage unit in some months (e.g. January or February) (Figure 5-14) and at many times even RES surplus, during the summer months (e.g. July and August) most of the peak energy supply is derived from the storage unit (Figure 5-15).

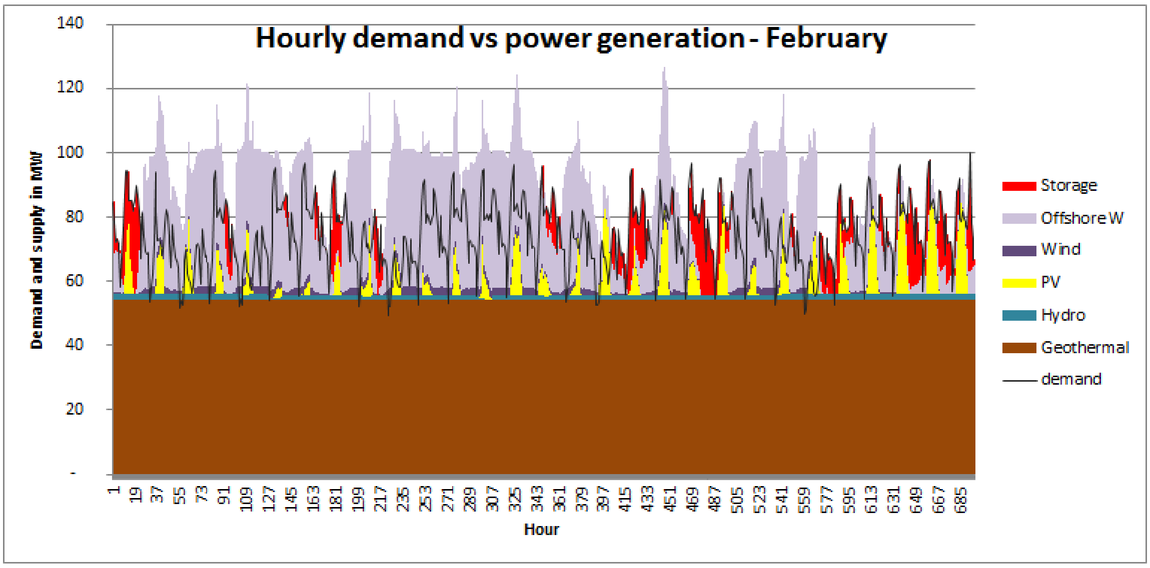


Figure 5-14: Demand-supply profile for February (Antevorta 30LS 100% RES)

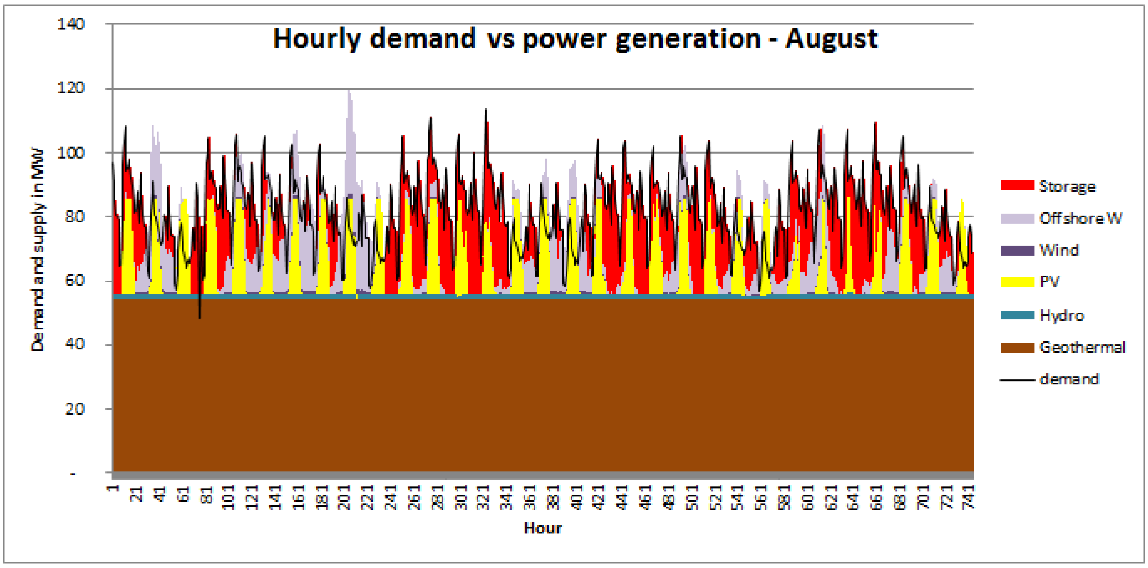


Figure 5-15: Demand-supply profile for August (Antevorta 30LS 100% RES)

The major challenge of a system based on 100% RES is defined through the need for backup at all times. The energy required during the peak summer season must already be generated during the winter months. Hence, the storage system steadily charges over the year (Figure 5-16). The result is a massively large (oversized) storage system that rarely interacts over short periods. Subsequently, the large storage system aggregates to the highest cost component of the overall system and influences the overall system cost profoundly.

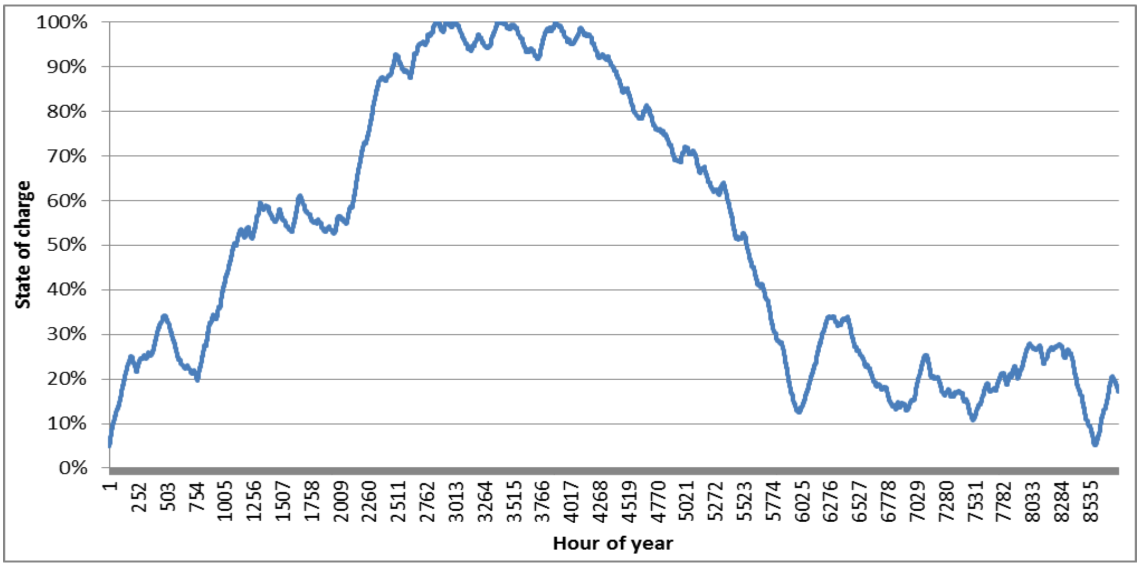


Figure 5-16: State of charge over the year (Antevorta 30LS 100% RES)

In order to provide some comparison of the energy system parameters across Antevorta LS30 it may be referred to Table 5-14. The results clearly highlight the major cost drivers of each alternative and in accordance with the results presented in Figure 5-12. The color scale for the cost comparison is introduced to ease the comparison of results and to identify the best solutions (red is highest and green is lowest cost). The capacities for base load RES are not listed in the table, since they do not change across the alternatives. In addition to the selected RES, the overall system cost changes noticeable with the size of the storage system parameters as well as the annual storage demand.

Table 5-14: Alternative comparison for Antevorta 30LS 100% RES

Variable RES combinations	Solar (MW)	Onshore wind (MW)	Offshore wind (MW)	Wave (MW)	Storage system		Annual storage demand (MWh)	Overall system cost (Mio. $)
					Power (MW)	Energy (MWh)		
Solar *	109.34	-	-	-	96.26	29,507	107,871	355.5
Onshore wind	-	86.84	-	-	75.52	33,169	74,865	395.9
Offshore wind	-	-	71.15	-	71.34	29,810	69,823	367.2
Wave	-	-	-	55.45	58.74	46,448	82,868	533.4
Solar and onshore wind	29.82	56.50	-	-	48.13	18,066	58,923	235.0
Solar and offshore wind	29.82	-	46.56	-	53.07	16,911	55,322	226.8
Solar and wave	29.82	-	-	36.62	53.54	30,802	64,225	368.2
Onshore wind and offshore wind	-	2.62	69.06	-	66.75	29,901	69,942	368.0
Onshore wind and wave	-	70.63	-	8.37	70.75	32,686	64,996	389.9
Offshore wind and wave	-	-	65.39	3.66	62.81	29,730	65,590	365.6
Solar, onshore wind and offshore wind	29.82	2.62	44.47	-	46.72	16,910	55,440	226.4
Solar, onshore wind and wave	29.82	55.45	-	0.52	50.49	18,240	58,385	236.4
Solar, offshore wind and wave	29.82	-	46.04	0.52	46.65	17,176	54,630	229.4
Onshore wind, offshore wind and wave	-	3.66	64.87	2.09	64.82	29,874	67,550	367.2
Solar, onshore wind, offshore wind and wave	29.82	2.62	42.90	1.05	56.19	17,233	54,412	230.1
Fossil fuel generation cost $100								122.4
Fossil fuel generation cost $150								183.6
* solar capacity exceeds the maximum limits; alternative does not lead to a solution								

In case only one variable RES is selected, the dependency of the system on the resource availability of that RES is the highest; and so are the costs. Consequently, more backup must be provided. As more variable RES are considered, the costs and storage parameters decrease. In the specific example the lowest cost can be achieved for 3 variable RES. In many other scenarios the alternative with the lowest overall system cost includes all 4 variable RES. Generally, a greater independence of resource availability between RES leads to lower system cost and smaller storage system parameters. The alternatives of variable RES indicate that combinations of solar and wind in combination with wave are most favorable. Any combination that does not include solar leads to significantly higher overall costs.

Reflecting the results of the MCDA performed in WP3 (Chapter 5.5 p. 135), the results of Table 5-14 may be applied for the final selection of a supply alternative according to the preferences of the DM. In the end, it does not necessarily need to be the alternative with the lowest cost, but one that includes the preferred RETs of the decision maker. The selection approach could be further improved by reflecting the capacities that were identified within each alternative in the attribute values and the criteria weights. Thereby, the investment cost and operation and maintenance cost may be substituted by the overall system cost. Then the swing weights have to be adjusted, whereas an increase from the worst to the best overall system cost presents the greatest satisfaction. All other criteria are ranked accordingly and the overall value functions of each alternative may be reassessed.

It is clear from the time series algorithm which analyzed solutions for 100% RES supply, and mainly from the performance of the storage system, that significant reductions of the overall system cost can be achieved by lowering the storage energy size and the demand for energy storage in general. Therefore, modifications of the time series have been performed to consider minor contributions (of up to 5%) of fossil fuels.

5.6.2. Supply alternatives with fossil fuel contribution

With the intension to build supply alternatives that are competitive with a system entirely driven by fossil fuels, modifications of the supply alternatives were undertaken. In accordance with the time series algorithm described in Chapter 3.3 (p. 56 ff.) fossil fuel contributions were introduced to the supply alternatives. While Aurora and Antevorta allowed up to 5% of the demand to be covered from fossil fuels, in Janus no limit was defined. The actual contribution is obtained from the availability of still active fossil fuel units and the demand that was pre-defined to be covered from RES (see establishment of load profiles in Chapters 3.2 and 5.3).

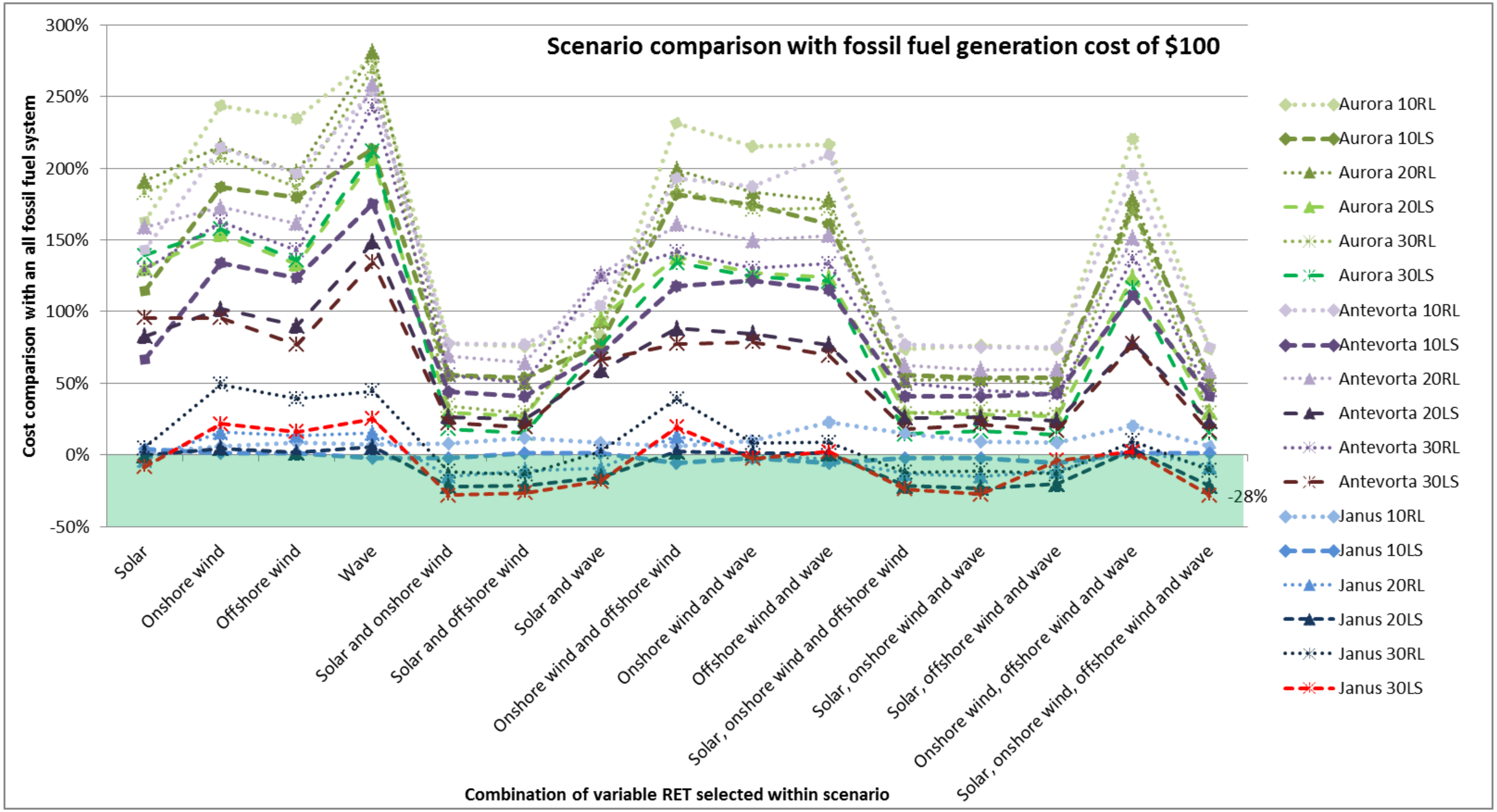


Figure 5-17: Cost comparison of all scenarios with fossil fuel generation cost of $100

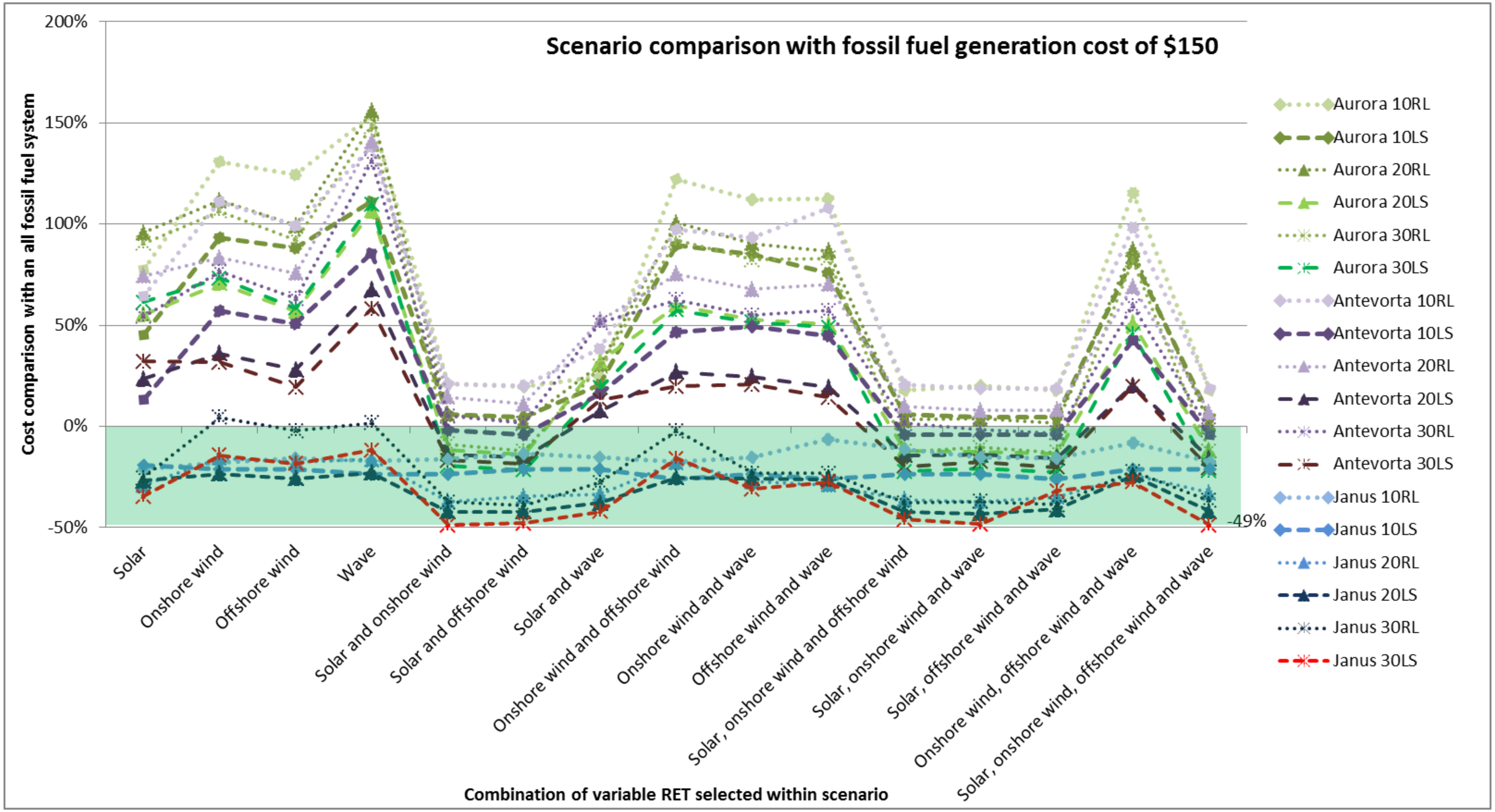


Figure 5-18: Cost comparison of all scenarios with fossil fuel generation cost of $150

In Figure 5-17 and Figure 5-18 the results with two different fossil fuel prices ($100 and $150) are presented for all scenarios. The contributions of fossil fuels for all Janus scenarios were assessed within the time series algorithm. In the 10 year time frame the contribution of fossil fuels is around 30-32% within all alternatives. In the 20 year time frame this percentage declines to 17-20% and in the 30 year time frame the percentage is as low as 9-14%. The lower end of the percentage always occurs for scenarios where load shifting is performed, since the ‘modification’ on the demand side causes an increase of the base load capacity limit (which is a major difference between the two load profile types).

The comparison across all scenarios provides a great amount of results.

- For the best alternative a label is added in both Figures.
- The higher contributions of fossil fuels in Janus always lead to lower overall system costs.
- In the long-term better results for all scenarios can be achieved.
- In the long-term the difference between the costs of higher (Janus) and lower (Aurora and Antevorta) fossil fuel contributions reduces.
- The difference of regular load profiles and ones with load shifting is clearly noticeable across all scenarios and alternatives. Savings between the two load profile types of the same scenario and time frame usually range from 20-40%.
- Fossil fuel generation cost of $100:
  - Only some alternatives for Janus become cheaper than a system that is entirely driven by fossil fuels. The only alternatives that results in lower costs are combinations where solar and at least one other variable RES are selected. Alternatives without solar always result in higher costs.
  - All alternatives for Aurora and Antevorta result in higher costs. The best alternatives for Aurora are around 14-16% higher than a fossil fuel system, and for Antevorta around 16-21%.
- Fossil fuel generation cost of $150:
  - Almost all alternatives for Janus are less expensive or at least very close to the cost of a system of solely fossil fuels.
  - In the 10 year time horizon none of the alternatives for Aurora achieves lower costs than a fossil fuel driven system.
  - In Antevorta only alternatives with solar and at least one other variable RES reach marginally lower costs, but only if load shifting is included.

    - The lowest costs within the 10 and 20 year time horizon are lower in Antevorta, when compared with Aurora. In the 30 year time horizon the best alternatives for Aurora are 2-10% better than for Antevorta. However, across all alternatives Antevorta provides lower and more balanced (difference between worst and best) results.
- Regular load vs. load shifting (at a fossil fuel generation cost of $150):
    - For alternatives with a regular load only Janus 20, Janus 30 and Antevorta 30 reach lower overall system costs than an all fossil fuel system.
    - If load shifting is included in Janus, than all alternatives lead to lower costs.
    - In Aurora load shifting leads to lower costs in the 20 and 30 year time frame for alternatives where solar and onshore or offshore wind are included.
    - For Antevorta the same observations can be made, with the difference that lower costs can already be achieved in the 10 year time horizon.
- It should be noted that despite the difference in demand that is associated to each of the load profiles, comparable overall system costs can be achieved. The slightly better performance of Aurora 30 compared to Antevorta 30 is the result of the higher energy demand due to the vector shift that is performed over time. In the end, it is important to emphasize that Antevorta provides cost competitive solutions, whereby more than three-fourth of the overall energy demand will be covered with RES based electricity.

Based on the overall system cost comparison it is decided to analyze 3 alternatives in detail: Janus 30LS which provided the lowest overall system cost as well as a comparison of Antevorta 30RL and Antevorta 30LS. The analysis of these scenarios takes into account fossil fuel generation costs of $150 per MWh.

The time series algorithm for Janus 30LS leads to the installation of 28.9 MW geothermal power and 0.51 MW of hydro capacity. 2.66 MW of hydro power is still operating. This represents the base load capacity limit which is exceeded in 90% of the hours of the year. Following the procedures of the time series algorithm the remaining capacities for the variable RES, the parameters of the storage system as well as the contribution of fossil fuels and energy spillage were identified. The results for each of these parameters are summarized in Table 5-15 (whereas a color scale is applied for the overall cost: green is best and red is worst). The share of fossil fuels in the generation mix ranges from 9-13%. The most noticeable changes in comparison with the results of a system based on 100% RES (compare with Table 5-14) supply occur for the storage energy size and the annual storage demand. As a matter of fact, the storage energy size can be reduced by a multiple of 70-150. Even though a limit on spillage is imposed, none of the alternatives comes close to the 5% hurdle.

Table 5-15: Alternative comparison for Janus 30LS

Variable RES combinations	Solar (MW)	Onshore wind (MW)	Offshore wind (MW)	Wave (MW)	Storage system Storage Power (MW)	 Storage Energy (MWh)	Annual storage demand (MWh)	Energy spilled (%)	Overall system cost (Mio. $)	% fossil fuel
Solar*	47.51	-	-	-	35.24	268	25,301	2.30%	62.4	12%
Onshore wind	-	33.00	-	-	28.04	478	12,877	4.19%	81.8	13%
Offshore wind	-	-	27.88	-	24.08	400	12,368	3.65%	78.0	12%
Wave	-	-	-	21.33	23.24	460	13,003	4.60%	84.3	13%
Solar and onshore wind	29.02	12.80	-	-	25.89	207	15,248	1.14%	48.9	9%
Solar and offshore wind	27.88	-	11.38	-	25.40	211	14,584	1.09%	49.9	9%
Solar and wave	29.02	-	-	8.25	20.98	238	13,786	1.85%	55.3	10%
Onshore wind and offshore wind	-	3.41	24.75	-	20.49	422	12,478	3.81%	80.3	12%
Onshore wind and wave	-	17.07	-	10.24	25.20	262	10,388	3.10%	65.9	11%
Offshore wind and wave	-	-	13.94	10.53	17.27	194	9,597	3.42%	69.2	12%
Solar, onshore wind and offshore wind	28.45	12.52	0.57	-	24.57	237	15,454	1.42%	51.6	10%
Solar, onshore wind and wave	28.73	12.52	-	0.28	25.18	202	14,957	1.22%	49.3	9%
Solar, offshore wind and wave	27.88	-	11.09	0.28	22.95	217	14,692	3.18%	65.1	11%
Onshore wind, offshore wind and wave	-	1.71	12.52	10.53	17.23	195	9,600	3.44%	69.2	12%
Solar, onshore wind, offshore wind and wave	28.73	12.23	0.28	0.28	25.52	205	15,057	1.14%	48.9	9%
Fossil fuel generation cost $150									95.5	

* solar capacity exceeds the maximum limits; alternative does not lead to a solution

The state of charge reflects the changes of the storage system clearly. A constant interaction of RES and the storage system occurs throughout the year (Figure 5-19). These high fluctuations within short periods indicate that the storage system is much better sized than in a supply scenario that is based on 100% RES.

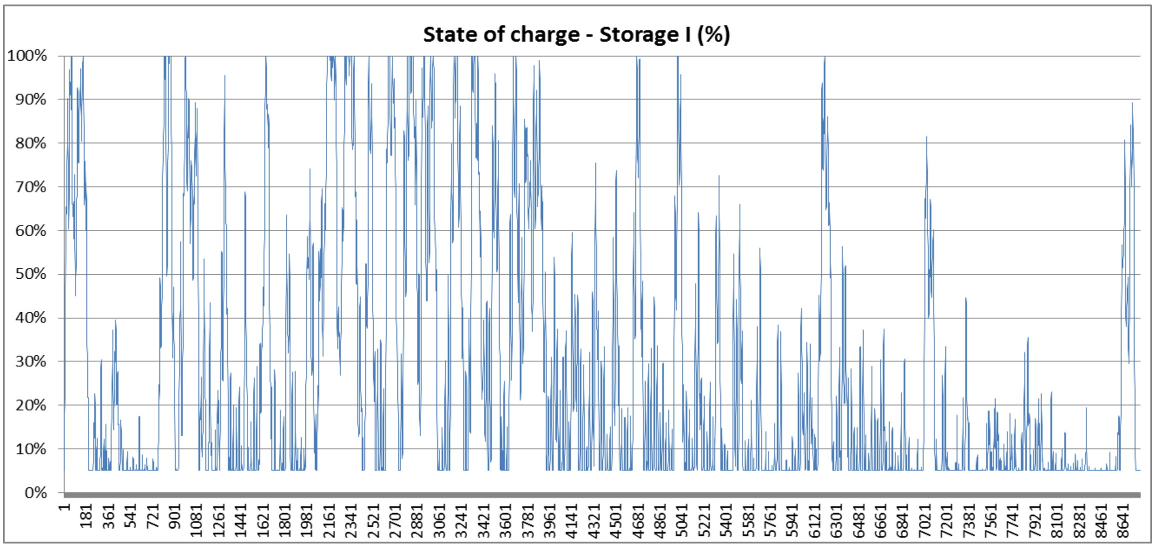


Figure 5-19: State of charge for storage system I (Janus 30LS)

In addition to the parameters listed above the demand for fossil fuels as well as a second storage system are assessed (Table 5-16). The second storage system is much smaller in, both, power and energy and provides an additional means of backup.

Table 5-16: Storage and fossil fuel parameters for alternatives of Janus 30LS

Variable RES combinations	Back-up capacity fossil fuel storage (MW)	Back-up energy fossil fuel storage (MWh)	Annual back-up from fossil fuel storage (MWh)	Total fossil fuel generation (MWh)	Energy spillage (MWh)
Solar*	15.03	69	5,008	43,236	8,612
Onshore wind	17.49	82	5,915	47,894	15,856
Offshore wind	20.87	81	5,625	44,396	13,738
Wave	21.40	65	4,785	50,179	17,554
Solar and onshore wind	13.85	77	4,288	33,885	4,153
Solar and offshore wind	14.05	80	4,326	33,478	3,987
Solar and wave	17.35	79	4,957	36,817	6,788
Onshore wind and offshore wind	24.17	100	5,557	46,465	14,368
Onshore wind and wave	15.80	72	4,883	41,441	11,546
Offshore wind and wave	20.69	101	5,245	44,541	12,833
Solar, onshore wind and offshore wind	14.30	70	3,631	34,858	5,206
Solar, onshore wind and wave	14.22	75	4,231	34,281	4,459
Solar, offshore wind and wave	12.10	44	1,391	42,277	11,862
Onshore wind, offshore wind and wave	20.69	101	5,260	44,644	12,908
Solar, onshore wind, offshore wind and wave	14.03	77	4,328	33,785	4,167

* solar capacity exceeds the maximum limits; alternative does not lead to a solution

The state of charge for both storage systems is shown in Figure 5-20. Since the analysis for the second (fossil fuel) storage system takes into account the inter-day generation of units, the second storage system remains at a very high state of charge for most hours of the year. Indeed, small contributions of storage II mainly occur during peak hours within each day.

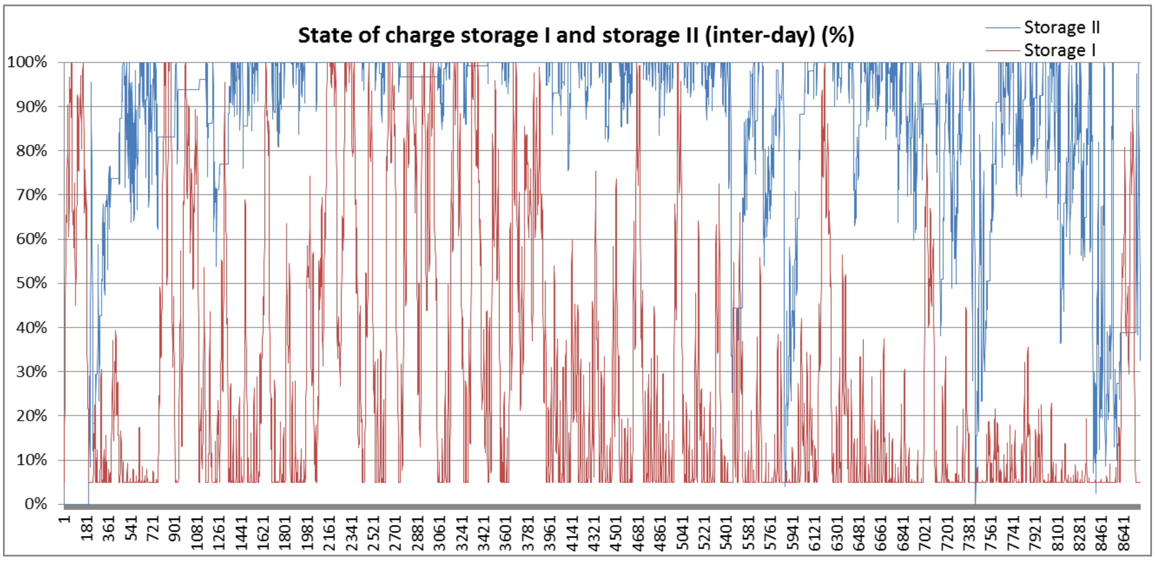


Figure 5-20: State of charge for storage system I and storage system II (Janus 30LS)

The inter-day analysis of the second storage system has been introduced since an intra-day analysis would lead to various hours within the year, where the storage system would be occasionally empty and additional fossil fuel demand would be required. This concern is presented in Figure 5-21 through periods with a 'negative' state-of-charge. Hence, in the inter-day analysis all system parameters are defined so that demand does not exceed the power and energy that is provided by the second storage system (see fossil fuel storage parameters in Table 5-16).

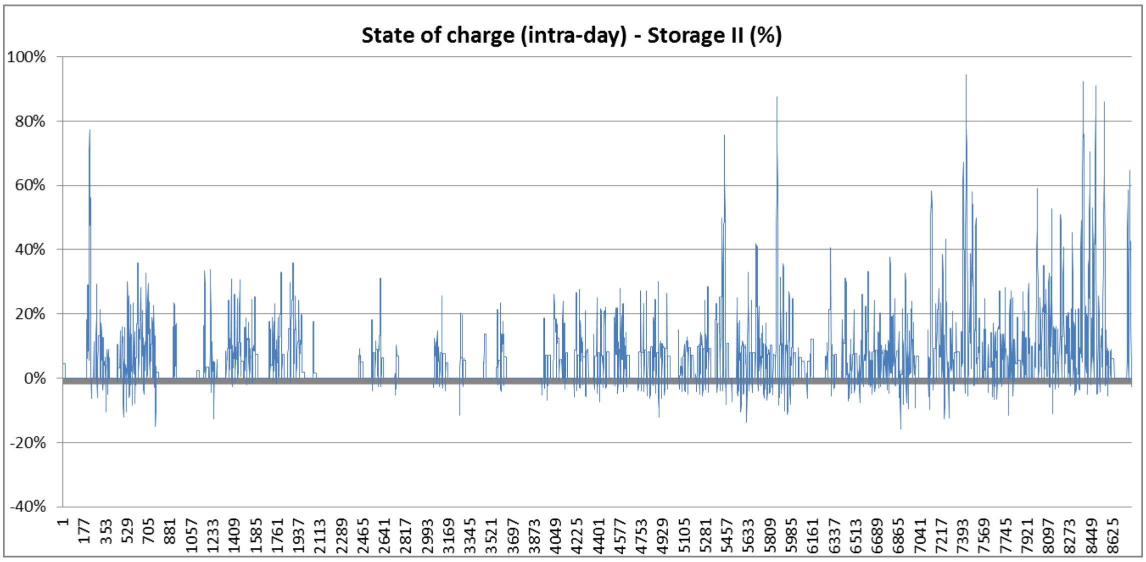


Figure 5-21: State of charge intra-day analysis for storage system II (Janus 30LS)

Lastly, a comparison of Antevorta 30RL and Antevorta 30LS is performed. All relevant energy system parameters are summarized in Table 5-17 and Table 5-18. While the overall energy demand to be covered is identical for both scenarios, it is the actual difference in the base load limits that causes a major variance. Since the time series algorithm starts with the identification of base load RES all other energy parameters are changed subsequently. The difference in the base load limits result from load shifting, whereas major peaks are shifted towards off-peak hours. As a consequence, the amount of hours that exceed a defined base load limit (90% of hours of year) is altered and a higher base load limit can be defined. Accordingly, the contribution of variable RES is reduced, which then also affects the storage parameters, demand for fossil fuels and the energy spillage. In conclusion, for future energy planning strategies, involving high levels of RES integration in the energy system, modifications of the energy system must first be undertaken on the demand side. This is a matter of energy sufficiency, whereas the actual needs have to be clearly defined, energy efficiency, whereas measures for savings are incorporated and reflected, and, finally, energy demand side management (DSM) strategies. DSM strategies are particularly valued to flatten and balance energy demand. In addition to the load shifting proposed in this research, further research on the effects of a flexible load shape is desirable, since it is strongly believed that a flexible load will have a direct impact on the overall demand-supply match. Less storage backup will be required and, thus, the costs of the overall system can be reduced.

Table 5-17: Alternative comparison for Antevorta 30RL

Variable RES combinations	Solar (MW)	Onshore wind (MW)	Offshore wind (MW)	Wave (MW)	Storage system		Annual storage demand (MWh)	Energy spilled (%)	Overall system cost (Mio. $)	% fossil fuel	Back-up capacity fossil fuel storage (MW)	Back-up energy fossil fuel storage (MWh)	Annual back-up from fossil fuel storage (MWh)	Total fossil fuel generation (MWh)	Energy spillage (MWh)
					Power (MW)	Energy (MWh)									
Solar *	143.80	-	-	-	116.71	16,503	99,894	3.41%	283.3	4.99%	28.63	162	4,782	36,602	25,051
Onshore wind	-	118.92	-	-	96.88	17,957	78,491	4.99%	323.9	3.55%	26.15	186	3,303	27,578	38,710
Offshore wind	-	-	97.68	-	95.47	13,665	71,933	4.98%	299.7	3.48%	27.98	198	3,690	26,799	38,270
Wave	-	-	-	75.24	69.45	27,326	79,265	5.00%	423.6	4.94%	30.75	155	3,936	38,597	39,037
Solar and onshore wind	29.73	86.76	-	-	84.52	3,826	54,719	4.76%	192.9	3.89%	26.91	138	3,693	29,043	35,542
Solar and offshore wind	29.73	-	70.99	-	64.55	2,365	46,877	5.00%	186.5	4.42%	27.70	130	3,753	32,955	37,222
Solar and wave	29.73	-	-	55.82	61.33	13,507	58,119	4.45%	277.6	4.65%	28.71	158	4,537	34,962	33,434
Onshore wind and offshore wind	-	1.21	96.47	-	95.46	13,602	71,939	4.95%	298.5	3.51%	27.95	198	3,698	26,993	38,042
Onshore wind and wave	-	81.91	-	19.42	99.29	13,146	55,895	4.97%	284.5	4.25%	25.82	186	3,483	32,443	37,896
Offshore wind and wave	-	-	83.12	9.10	90.28	12,377	61,350	4.98%	288.5	3.94%	26.00	181	2,888	30,078	38,042
Solar, onshore wind and offshore wind	29.73	3.03	68.56	-	62.06	2,602	48,175	4.84%	186.5	4.25%	27.69	130	3,598	31,608	35,968
Solar, onshore wind and wave	29.73	70.38	-	8.49	67.27	2,663	43,170	4.79%	180.4	4.42%	27.90	139	4,150	32,775	35,534
Solar, offshore wind and wave	29.73	-	64.31	4.25	52.86	2,065	42,669	4.82%	177.3	4.38%	25.44	140	4,028	32,458	35,721
Onshore wind, offshore wind and wave	-	4.25	84.34	6.07	83.16	13,109	65,152	4.89%	292.9	3.74%	27.07	191	3,106	28,584	37,426
Solar, onshore wind, offshore wind and wave	29.73	69.77	0.61	8.49	72.68	2,686	43,309	4.75%	180.6	4.35%	28.15	142	4,237	32,220	35,222
Fossil fuel generation cost $150									183.6						

* solar capacity exceeds the maximum limits; alternative does not lead to a solution

Table 5-18: Alternative comparison for Antevorta 30LS

Variable RES combinations	Solar (MW)	Onshore wind (MW)	Offshore wind (MW)	Wave (MW)	Storage system		Annual storage demand (MWh)	Energy spilled (%)	Overall system cost (Mio. $)	% fossil fuel	Back-up capacity fossil fuel storage (MW)	Back-up energy fossil fuel storage (MWh)	Annual back-up from fossil fuel storage (MWh)	Total fossil fuel generation (MWh)	Energy spillage (MWh)
					Power (MW)	Energy (MWh)									
Solar *	109.34	-	-	-	94.00	10,847	81,246	3.75%	242.7	5.00%	26.85	50	1,150	36,667	27,520
Onshore wind	-	86.84	-	-	69.44	8,834	51,421	4.94%	241.7	3.57%	23.95	97	2,553	26,940	37,269
Offshore wind	-	-	71.15	-	61.97	5,609	46,430	4.88%	218.8	3.49%	25.79	109	2,816	26,075	36,446
Wave	-	-	-	55.45	54.54	14,807	51,468	4.99%	290.4	4.90%	21.03	82	2,399	37,366	37,994
Solar and onshore wind	29.82	56.50	-	-	35.93	1,429	34,250	4.72%	152.7	4.48%	19.54	46	1,704	32,875	34,607
Solar and offshore wind	29.82	-	46.56	-	40.13	973	30,576	4.77%	149.5	4.82%	14.63	31	1,151	35,323	34,967
Solar and wave	29.82	-	-	36.62	45.09	6,055	38,136	4.62%	207.2	4.95%	13.83	30	1,067	36,559	34,120
Onshore wind and offshore wind	-	2.62	69.06	-	61.67	5,631	46,522	4.94%	219.8	3.52%	25.46	106	2,737	26,366	36,941
Onshore wind and wave	-	70.63	-	8.37	65.98	6,506	39,698	5.00%	221.6	3.94%	23.17	86	2,554	29,481	37,350
Offshore wind and wave	-	-	65.39	3.66	57.93	4,716	41,250	5.00%	209.8	3.70%	25.27	103	2,848	27,566	37,290
Solar, onshore wind and offshore wind	29.82	2.62	44.47	-	40.23	981	30,694	4.61%	147.1	4.58%	15.91	38	1,545	33,539	33,720
Solar, onshore wind and wave	29.82	55.45	-	0.52	43.09	1,228	32,489	4.84%	151.6	4.76%	15.03	43	1,680	34,956	35,582
Solar, offshore wind and wave	29.82	-	46.04	0.52	40.82	835	29,199	4.79%	146.6	4.72%	15.56	37	1,600	34,633	35,109
Onshore wind, offshore wind and wave	-	3.66	64.87	2.09	60.55	5,635	44,153	4.99%	219.8	3.71%	23.83	93	2,269	27,770	37,282
Solar, onshore wind, offshore wind and wave	29.82	2.62	42.90	1.05	40.69	831	28,789	4.74%	145.5	4.77%	15.41	38	1,596	34,973	34,711
Fossil fuel generation cost $150									183.6						

* solar capacity exceeds the maximum limits; alternative does not lead to a solution

The base load capacity limits for Antevorta 30RL and Antevorta 30LS are 54 MW and 62 MW respectively, whereas 3.77 MW (Antevorta 30RL) and 3.33 MW (Antevorta 30LS) are hydro power. The remainder in these two scenarios is geothermal power. After having defined these base load limits all procedures of the time series algorithm were performed accordingly so that the energy system parameters, as presented in Table 5-17 and Table 5-18, could be obtained.

The major differences between the two scenarios can be summarized as:

- The overall demand for variable RES is noticeably different.
- The overall system costs are very divergent, whereby the cost difference in the best cases is around $30 Mio. In comparison with entirely fossil fuel driven systems, both scenarios provide competitive or even less expensive solutions. The applied color scales help identifying the best alternatives within each scenario, whereby green presents low and red presents high costs.
- All storage parameters for Antevorta 30RL are much larger than for Antevorta 30LS. The power rating of the RES storage system of the different alternatives for Antevorta 30RL is between 25-130% higher than that for Antevorta 30LS. Similarly, the energy size of the alternatives differs by a factor of 2 to 3 between the two scenarios. However, the actual difference in the annual storage demand is much lower, whereas deviations between the scenarios are lower than 70% for all alternatives. This has in consequence that the storage system of Antevorta 30LS is used more frequently. Hence, even lower storage system costs per operating unit can be associated.
- Similarly to the RES storage system, the capacity and energy size of the fossil fuel storage system are largely deviating. As the second storage system is sized to just match any demand-supply disparity, it is expected that the annual contribution of the second (fossil fuel) storage system is much smaller than for the first one (RES storage). As a matter of fact, the results prove this assumption, since the annual storage demand in Antevorta 30RL is a multiple of the annual contribution in Antevorta 30LS. Again, this fact is directly related to the more balanced load profile of Antevorta 30LS.

However, both scenarios have also several similarities:

- In both cases the limit for the solar capacity is set to 30MW and is both scenarios all alternatives with solar try to reach that limit. Despite being the most favored

RES in the MCDA, this also shows that the solar RES availability in relation with the cost is the most suitable variable RES.

- The fossil fuel and/or spillage limits (5%) are almost reached in all alternatives. If the 5% limit is reached, this indicates that further increases of fossil fuels would lead to decreases in the overall system cost. The exact limits have not been identified, since the ambition of this research is to reach very high shares of RES contribution.
- However, there are some cases where neither the spillage nor fossil fuel limits are reached. In such cases a further increase of the fossil fuel contribution might only lead to marginal improvements in the overall system cost. Since the RES capacities are defined and operated according to the resource availability, any increase in fossil fuels would eventually cause more spillage.

When analyzing the graphical results of the time series algorithm the effects of the fossil fuel storage system become more obvious. Figure 5-22 and Figure 5-23 demonstrate the demand-supply profiles for February and August. In February most of the demand is met through RES. Surplus from RES is used within the next days (red storage section in Figure 5-22) or causes spillage (see Figure 5-24). The spillage, as displayed for February, results almost entirely from RES, since fossil fuel units are only scarcely operated (fossil fuel storage is already completely charged) and the RES energy storage is fully charged in many hours of the month.

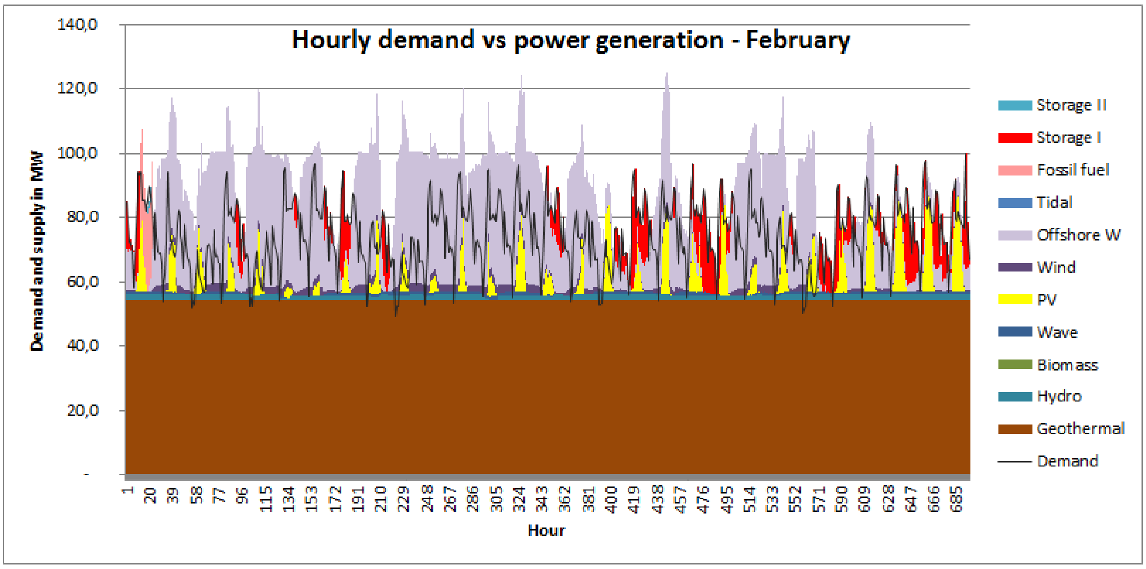


Figure 5-22: Demand-supply profile for February (Antevorta 30LS includes fossil fuel)

In August, when there is no or only limited wind available for most of the time, fossil fuels contribute more excessively to meet energy demand. At this stage the RES storage system is nearly discharged in most hours. Any RES surplus during these days is withdrawn from the storage as soon as the next supply deficit occurs. At the same time, fossil fuel units interact more frequently with the system. This in turn also causes spillage, since the fossil fuel units oftentimes have to start in the hour before their actual operation. Then the portion of RES energy that has been generated, but is now 'overtaken' by fossil fuel, is spilled. Additionally, spillage from fossil fuels must be taken into account for all hours where fossil fuel generation is greater than the demand for fossil fuels and/or when the fossil fuel storage is already fully charged (Figure 5-25).

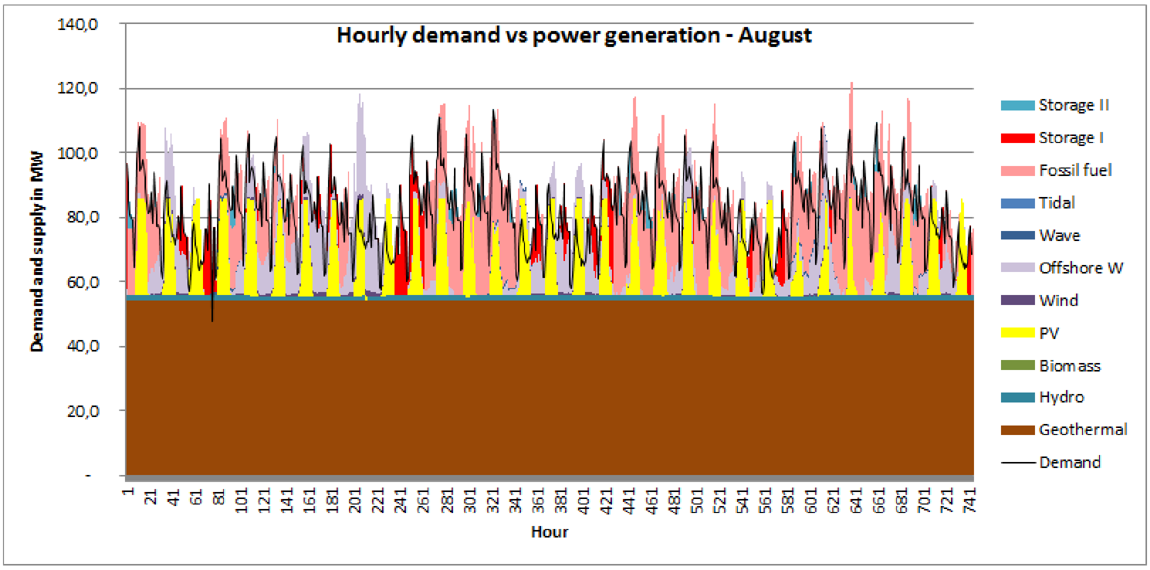


Figure 5-23: Demand-supply profile for August (Antevorta 30LS includes fossil fuel)

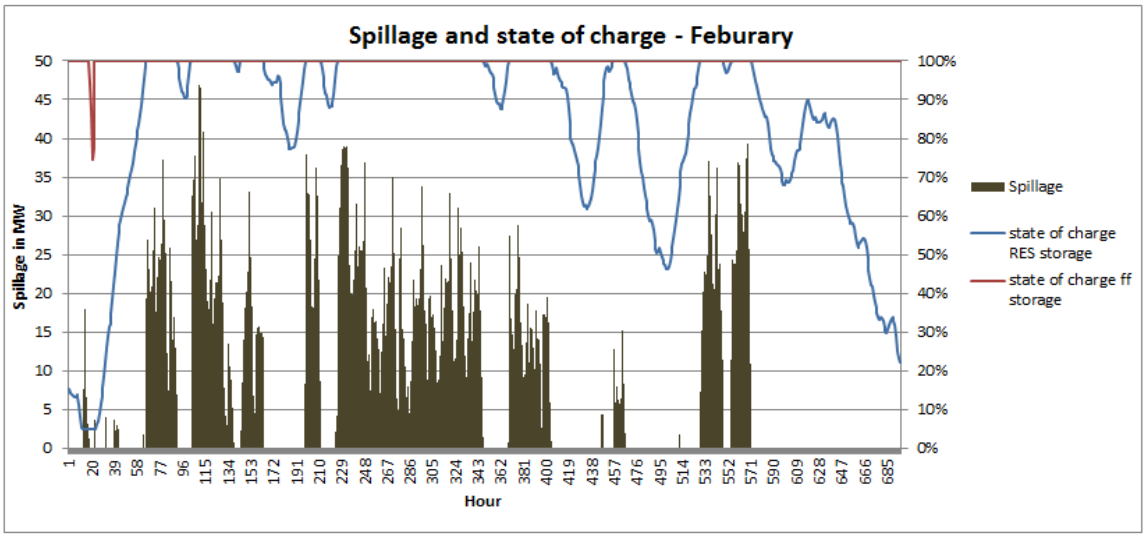


Figure 5-24: Spillage and state of charge in February (Antevorta 30LS includes fossil fuel)

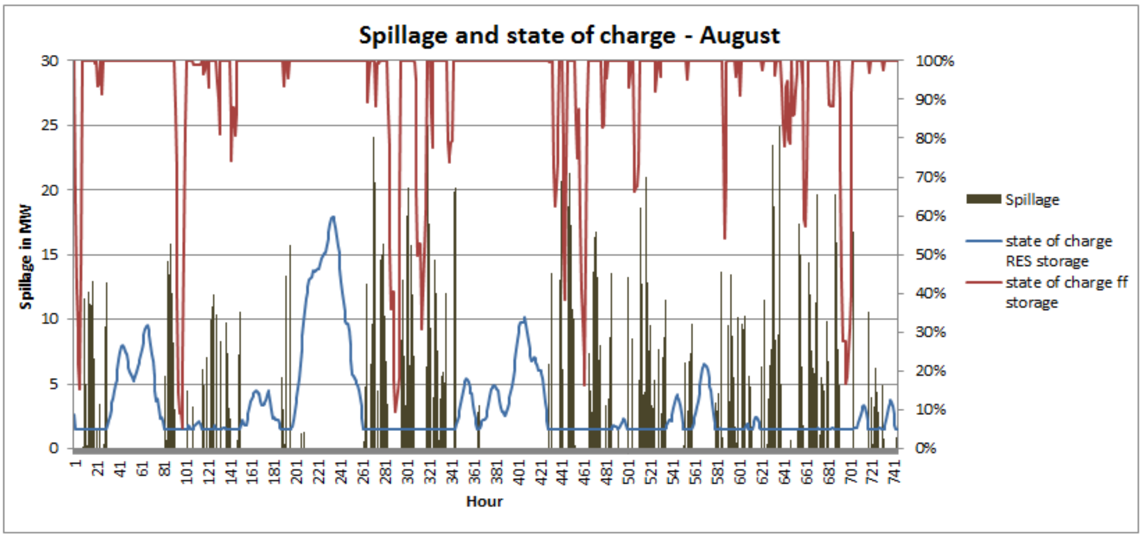


Figure 5-25: Spillage and state of charge in August (Antevorta 30LS includes fossil fuel)

5.6.3. Sensitivity analysis for contribution of base load RES

Within the initial analysis the maximum base load capacity was kept very low. It was surpassed in 90% of the hours of the year. Indeed, for many islands around the world it already presents a challenge to install such a great amount of base load RES, mainly because they do not possess such colossal geothermal resource availability like São Miguel. Therefore, most islands need to rely on a diverse RES portfolio, whereby high shares of variable RES are oftentimes the only alternative to reduce fossil fuel dependency. São Miguel is a very distinct case and provides a geothermal energy source far greater than the islands energy requirements. Consequently, modifications of the maximum base load have been performed to assess the effects on the overall system cost as well as the storage system.

In Figure 5-26 a comparison of the maximum base load capacities is performed for Antevorta 30RL. The regular load shape scenario was selected, since it comprises a greater variation of the daily maximum and minimum load. Hence, greater interactions of base load RES and the storage system along with higher overall system costs compared to a scenario with load shifting are expected. The results show that an increase in the maximum base load capacity leads to lower overall system costs. In fact, the costs for a system that is entirely driven by base load RES and using a regular load profile (for instance geothermal and hydro energy like on São Miguel) are noticeably lower than for a system which also includes variable RES.

If the energy demand is 100% RES based, then none of the alternatives is cost competitive with an 'only' fossil fuel system. Even if only base load RES and a pumped hydro storage system are selected, the overall system costs remain around 45% higher than a fossil fuel system with generation costs of $100 per MWh.

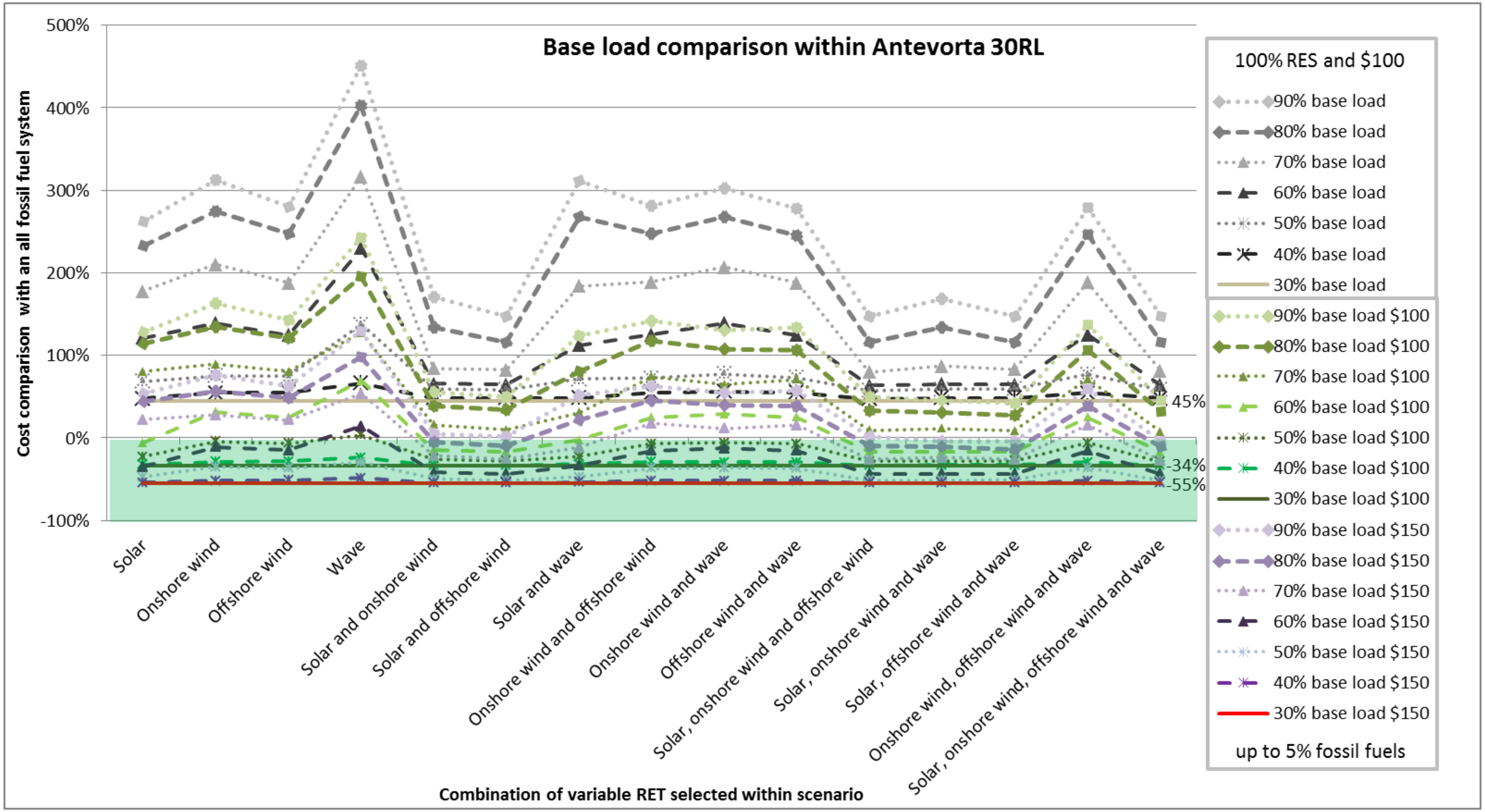


Figure 5-26: Cost comparison for varied maximum base load capacities within Antevorta 30RL

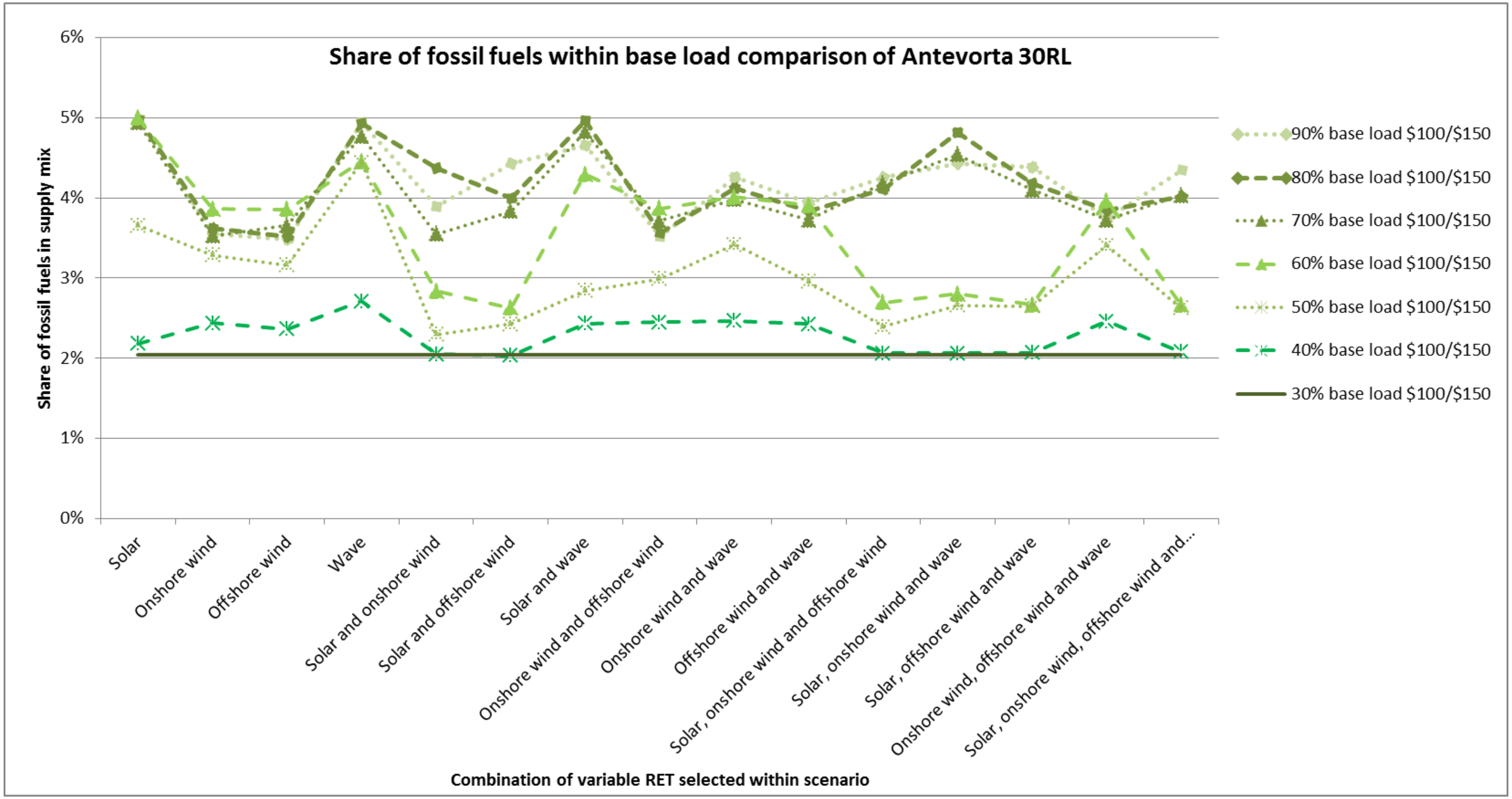


Figure 5-27: Comparison of fossil fuel contribution for varied maximum base load capacities within Antevorta 30RL

However, the inclusion of small shares of fossil fuels has been assessed. With higher shares of variable RES solutions tend to come close to the imposed 5% hurdle. But, an increase in the base load RES lowers the fossil fuel contribution to around 2% (Figure 5-27). In fact, even the combination of several variable RES limits the fossil fuel contribution, whereas the major differentiation occurs if the base load limit is exceeded in more than 60% rather than 70% of the time.

Bearing in mind the contribution of fossil fuels as indicated in Figure 5-27, the results in Figure 5-26 also highlight that with a 90% base load limit and a small contribution of fossil fuels, the best alternatives are economically more attractive than an alternative that is based on 100% base load RES (compare solid grey line of 30% base load with dotted light green line of 90% base load $100). Subsequently, for islands that do not have such favorable natural resource availability like São Miguel, it is always an alternative to aim for very high shares of RES (a mix of base load RES but also variable RES) along with a minor contribution of fossil fuels.

The major drivers for the reduced costs of the different base load scenarios can be demonstrated with the quantity of RES capacities installed as well as with the size of the storage parameters. Indeed, a high base load capacity provides much greater planning security, since the energy system mainly charges and discharges throughout the day rather than over the days and weeks or even months. The state of charge of the storage systems in Figure 5-28 illustrates that the storage system interacts over much shorter periods and more harmonically (compare with Figure 5-20 p. 147). Due to the sizing of RES the fossil fuel storage system will mainly interact during summer months when the major peaks occur and when the daily peak load demand is extended over longer periods.

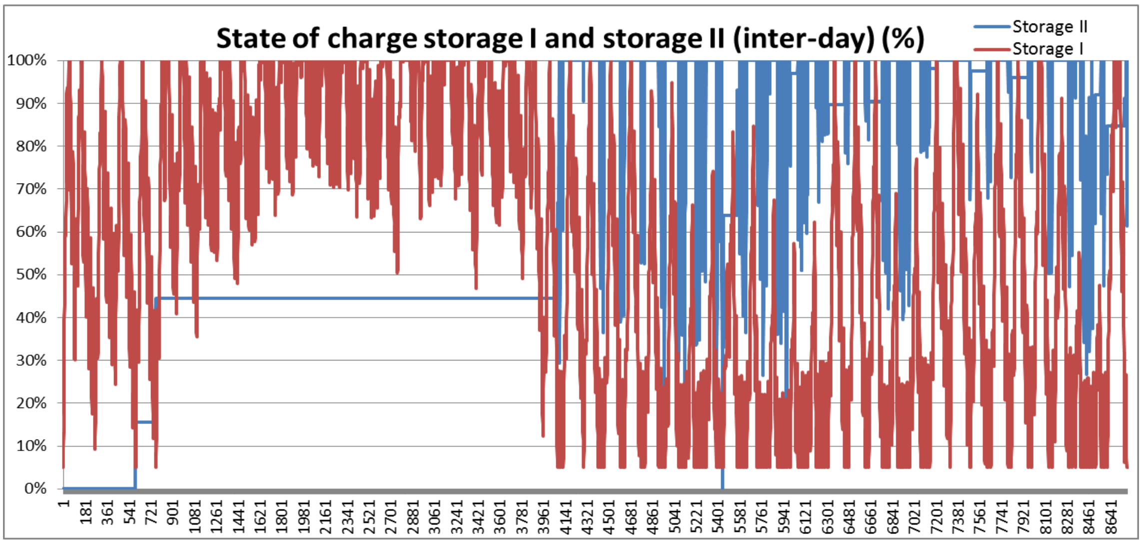


Figure 5-28: State of charge for storage system I and storage system II (Antevorta 30RL)

The load profiles in Figure 5-29 and Figure 5-30 show the daily interaction more precisely. While in August the peak demand is regularly greater than the surplus generation of base load RES during off-peak hours, in November the balance between peak and off-peak hours is more convergent. Hence, less fossil fuel contribution is required. The storage system basically charges during night and discharges during the day.

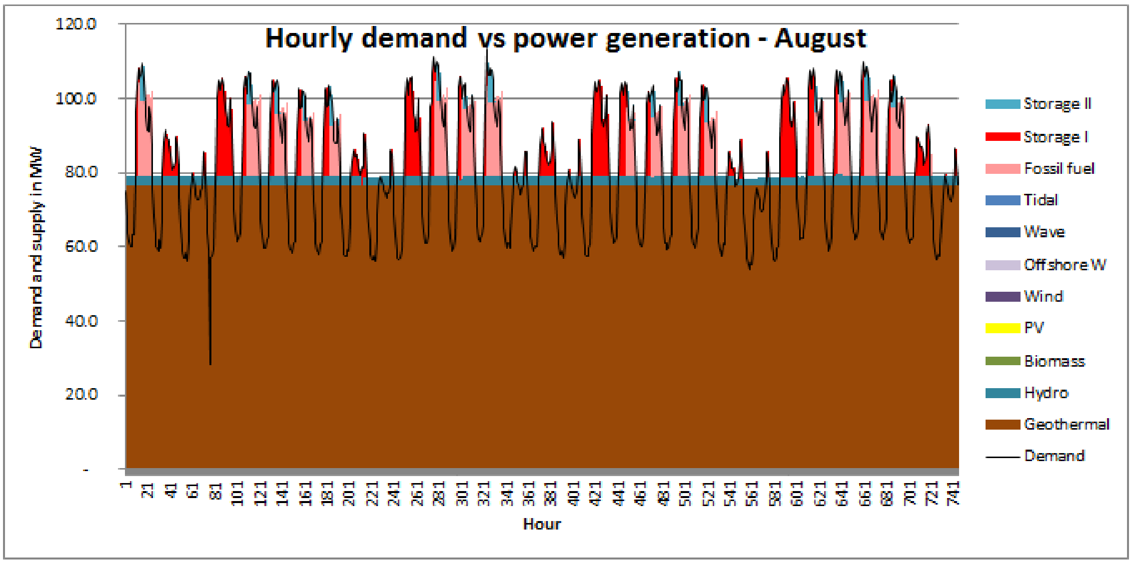


Figure 5-29: Demand-supply profile for August (Antevorta 30RL includes base load RES and fossil fuel)

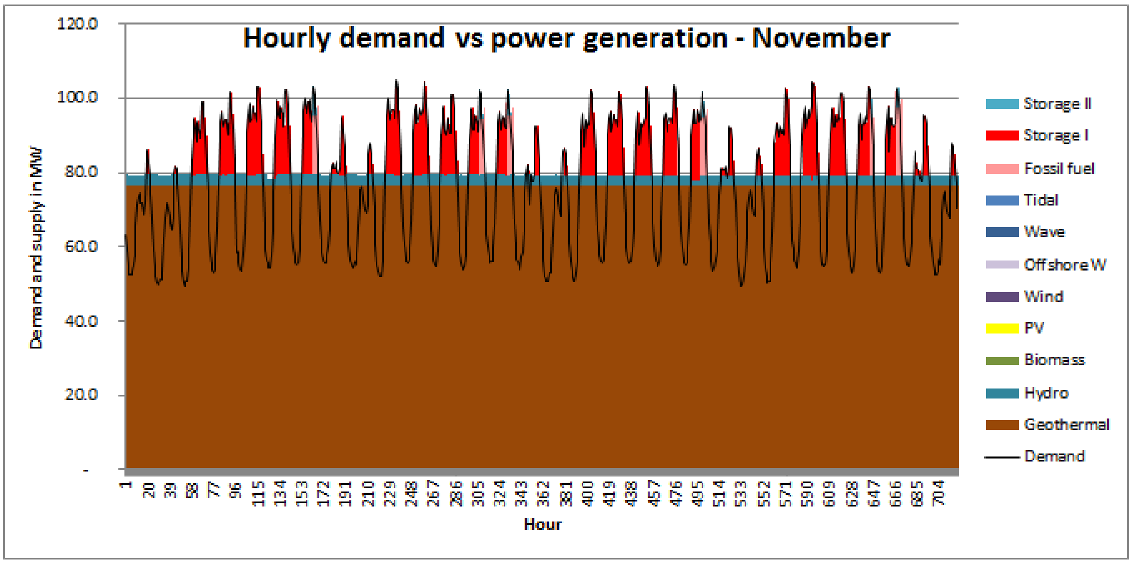


Figure 5-30: Demand-supply profile for November (Antevorta 30RL includes base load RES and fossil fuel)

This more harmonized interaction between surplus base load RES generation and the storage system can also be demonstrated with the state of charge profile for November (Figure 5-31). Only for a few hours within the month the energy supply will be based on fossil fuels and the second storage system respectively. Besides, the spillage is also very small.

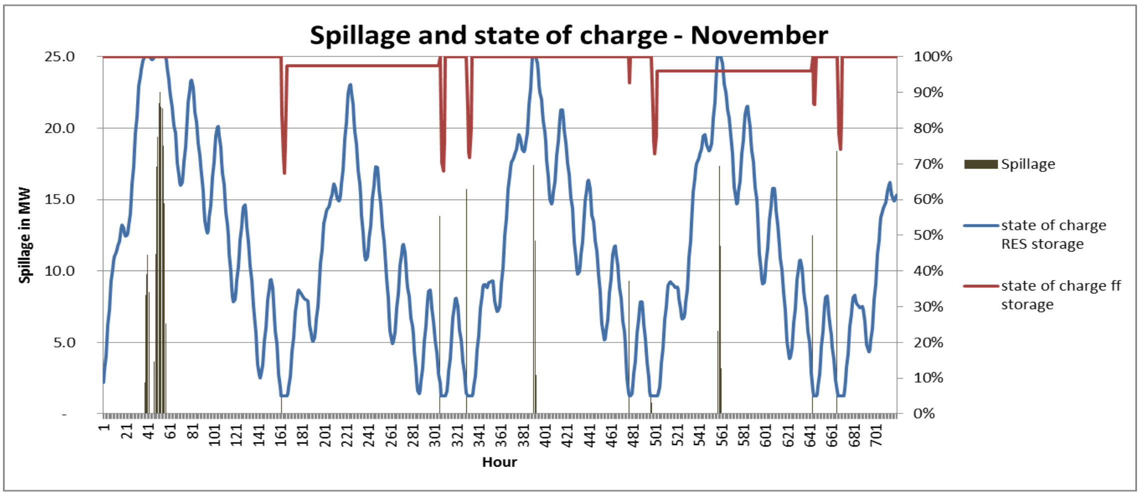


Figure 5-31: Spillage and state of charge in November (Antevorta 30RL includes base load RES and fossil fuel)

Lastly, a comparison of the absolute numbers is made for the best solution with variable RES and a base load limit that is exceeded 90% of the time (results from Antevorta 30LS) versus a supply alternative that is entirely driven by base load RES (Antevorta 30RL). In the upper section of Table 5-19 the RES capacities are listed, highlighting that a major part of the cost must be associated to the substantially higher capacities that are installed for variable RES, compared to only base load RES. Indeed, in the presented comparison the total capacity of RES is around 45 MW higher in the alternative with variable RES. This in fact bears a major burden on the higher system cost, since most of the variable RES operate at a noticeable lower capacity factor than base load RES and, thus, require higher capacities to be installed. Another major cost driver is the size of the storage system, both in terms of power and energy. Besides, considerable savings can be achieved in the only base load RES scenarios, since energy spillage has been penalized across all scenario and alternatives.

Table 5-19: Comparison of alternatives for only base load RES versus base load and variable RES

RES combinations	Hydro (MW)	Geothermal (MW)	Solar (MW)	Onshore wind (MW)	Offshore wind (MW)	Wave (MW)	Storage system Power (MW)	Storage system Energy (MWh)	Annual storage demand (MWh)	Energy spilled (%)	Energy spillage (MWh)
Best alternative for base load and variable RES	3.33	60.35	29.82	2.62	42.90	1.05	40.69	831	28,789	4.74%	34,711
Only base load RES	5.90	85.00	-	-	-	-	32.49	464	42,514	1.93%	13,671

RES combinations	% fossil fuel	Back-up capacity fossil fuel storage (MW)	Back-up energy fossil fuel storage (MWh)	Annual back-up from fossil fuel storage (MWh)	Total fossil fuel generation (MWh)	Overall system cost (Mio. $) at $100 fossil fuel generation cost	Overall system cost (Mio. $) at $150 fossil fuel generation cost
Best alternative for base load and variable RES	4.77%	15.41	38	1,596	34,973	142.3	145.5
Only base load RES	2.04%	11.36	49	1,953	14,499	80.8	82.1
Fossil fuel generation cost						122.4	183.6

In the lower section of Table 5-19 the fossil fuel contribution and second storage system are compared. While for the backup capacity and total fossil fuel generation the only base load

RES alternative is favorable, the backup energy size and annual backup from fossil fuel storage are in favor of the mixed supply alternative. In the overall system cost the only base load RES is the dominant alternative. Even with considerably lower fossil fuel prices, an only base load RES alternative is still competitive. If high shares of variable RES are integrated in the system then fossil fuel generation costs should be preferably above $120 per MWh to make an alternative cost-competitive.

The results of the above analysis demonstrate that the proposed time series algorithm provides a compact model for decision makers and energy planners. Different aspects of energy planning, such as different load profiles, different development trends of energy demand, different levels of base load and variable RES as well as various time horizons with different cost-development trends for RETs are combined in a single energy planning model.

Several crucial planning aspects, such as the technologies and the amount of each RES, can be defined and analyzed. It still presents a major challenge in energy planning to deal with high levels of RES integration. While the model allows to identify solutions based on 100% RES, it also provides thoughtful alternatives with small contributions of fossil fuels. Yet, the model offers results that can be compared across time.

In order to cope with the planning aspects that are of greatest importance for power system engineers, it was thought of a method to include and reflect the effects of unit commitment constraints. A modified algorithm has been developed that plans with small contributions of fossil fuels and includes a second storage system that solely interacts with the thermal generators. In that way it was possible to increase energy security, while only having a small share of fossil fuels in the system. For island energy planning, but also in general, this presents a great alternative to identify supply solutions, whereas the overall system costs are comparable to systems that are entirely based on fossil fuels.

Since space limitations, either due to ‘NIMBY’ issues or through conservation and heritage sites, often occur on islands, it was tried to provide solutions where offshore technologies are integrated. In the specific case of São Miguel various solutions could be found, where offshore wind and wave contribute significantly to the energy supply portfolio. However, due to the specific conditions of resource availability São Miguel can be supplied by large quantities of base load RES, mainly geothermal energy, in combination with a storage system (e.g. pumped hydro storage).

6. Conclusions

The last chapter of this thesis concludes the work. It summarizes the main results and findings and provides ideas and concept improvements for future work.

6.1. Summary of findings

This research presents a thoughtful energy planning model for decision makers of isolated systems that seek decision support for strategic planning. The model can be seen as the infrastructure for future energy planning, whereas several optimization models and/or tools may be applied thereafter. Within the proposed strategic model specific consideration was paid to the solution outcomes over time. Analysis of, both, the demand and supply side can be performed to address diverse interests that an applicant might find important when planning for a future energy supply scenario.

The proposed model can be clustered in four individual, yet dependent work packages. The analysis on the demand side focused on development trends and how the future demand profile might behave. In accordance with common practice, energy saving measures were discussed. However, it is essential, before applying any saving measures, to apply concepts of energy sufficiency, whereby the essential energy needs, for instance per capita, have to be (re)defined. Nowadays, it is very common in developed countries to use more energy than needed. This is often a problem of 'too' much comfort, whereas the energy consumption per capita is clearly higher than what one would actually need. Further research in the concept of energy sufficiency is highly encouraged, since this could provide another starting point for demand development scenarios. Yet, and also in this research, the base was formed by the current energy demand, whereby the per capita consumption of the 'essential' energy needs was neglected. A variety of saving measures were then introduced, highlighting the great potential for energy savings on the demand side. It is expected that in the upcoming decades further significant reductions can be achieved. As a matter of fact, if energy demand only increases marginally over the years, like in the case of São Miguel, an application of a wide range of energy saving measures might even lead to a lower energy demand than the current level.

Electricity has been identified as the most flexible energy vector. Since electricity can be provided from all RES, the ambition of this research was to identify supply solutions with very high shares of RES. In the most rigorous scenario up to 100% of electricity demand should be covered from RES. However, it is seen on a regular basis that electricity accounts for less than 40% or 50% of many countries total primary energy demand. This presents a great opportunity for RES, especially when considering the losses of fossil fuel conversion from primary to final energy. Besides, electricity at the end-user level is also more efficient than heat or fuel derivatives for transportation. Consequently, an assessment was performed to analyze how the future energy demand could be dominated by electricity from RES. While it was not the intension to cover all energy with RES based electricity, very high shares of 70% and more were aimed for. The remaining part of energy could then also be provided from other heat and fuel generating RES. In order to increase the share of electricity in the overall system, vector shifts were introduced across all sectors, excluding the industry. Thereby, increasing vector shifts were performed over time, since it is expected that more and more end-uses can be covered with electricity. This in turn might lead to noticeable increases in the future energy (electricity) demand and confirms the second hypotheses.

Since it is a common problem for energy planners and even utility operators, another analysis focused on demand side management strategies. Load shifting has been identified as an important measure to flatten and balance the load. In addition, it was thought of measures for a flexible load shape. However, at the current stage it is uncertain how the effects of a flexible load shape could be expressed in a monetary value. Therefore, flexible loads are considered for future work. In contrary, load shifting defines a clear set of shifts from one hour to another. Commonly shifts are performed from peak to off-peak hours. As the smart grid concept further develops and spreads more load shifts and higher load flexibility become reasonable. Indeed, further studies on the end-user behavior and awareness can have a significant impact on the RES integration. Especially in combination with RES forecasting on the supply side modifications on the demand side will allow for a better convergence of the load.

In the end, development trends, shifting measures, saving measures and demand side management strategies were combined to build future demand scenarios. The variety of features considered, provides applicants of the model with an opportunity to reflect several demand development trends they may be interested in.

The selection of supply technologies is a crucial procedure for decision makers. In many cases, ambitious projects have failed since they did not reflect upon the local conditions. Therefore, this research proposed an assessment of the resource availability and site characteristics in the first place. Only RETs that meet the introduced conditions are considered for further evaluation. Indeed, each RET has been analyzed in depth, so that its suitability could be characterized with technology-specific conditions. By means of an algorithm, which applied binaries (yes/no) for each condition, all RETs could be assessed accordingly. One of the major challenges of this procedure is the amount of site specific data that is required to perform the analysis. It has been a challenge within this research to find adequate data and characteristics to analyze the conditions for São Miguel. Hence, it is believed that for more remote islands the major obstacle is imposed by finding adequate data of the local sites.

After the RETs are pre-selected, multi-criteria decision analysis in the form of multi-attribute value theory is applied to assess the technologies according to the preferences of the decision maker. Thereby, swing weights were applied to reflect the DMs criteria weights. Initially, a large set of data (attributes) had to be gathered for each criterion and the various RETs. Since long-term planning strategies shall be analyzed, development trends were associated to each attribute to reflect the improvements over time. The results show two clear favorites: hydro and solar. Wind, offshore RES and geothermal performed more alike, whereas bioenergy remained in the bottom spot across most alternatives and all time horizons. While the MCDA assessed the overall performance of each RET, the resource availability and site characteristics also have to be accounted for. In the specific case of São Miguel, the potential to use geothermal energy is significant. Hence, geothermal energy should always be considered as a base load alternative. The remaining load in each scenario shall then be covered from variable RES and energy storage (and, if necessary, thermal units).

With the technologies identified from the pre-selection and bearing in mind the results of the MCDA, the time series algorithm was performed. Therefore, solutions were sought to cover energy demand based on 100% RES. The results clearly indicate that a 100% RES supply would accumulate massive costs as well as an extremely large storage system. Therefore, modifications of the algorithm were performed and a minor contribution of (up to 5%) fossil fuels was allowed in the system. This immediately resulted in much lower overall system costs, whereas solutions could be found across all scenarios so that the overall system cost could be competitive with a system that is entirely based on fossil fuels. As a matter of fact, in the long-term all scenarios, including their different development trends, shifting considerations and managements strategies, provided solutions with lower overall system costs. Thereby, it was a combination of solar with at least one additional intermittent RES that led to the best solution within each scenario. Individual or combinations without solar could not reach system costs that are comparable with an all fossil fuel based system. Even though the proposed algorithm follows a very strict, defined set of rules, which is not common to many energy planning models/tools, it provides a great and reflective variety of results that are important for any energy planner. In the final modifications of the algorithm unit commitment constraints were imposed and a second (fossil fuel) storage system was introduced. The results clearly demonstrate energy supply based on 100% RES is a matter of cost. However, with only small contributions, as much as 5%, a complete turnaround of the cost comparison with an entirely fossil fuel driven system can be achieved. This should be encouraging for many islands around the world, since it highlights that in the new energy paradigm fossil fuels can only be a marginal contributor. The core of any new system should be built around RES.

In distinct cases, like on São Miguel, where a great geothermal resource availability is given, high shares of base load RES are encouraging. Indeed, the sensitivity analysis demonstrated that supply alternatives that are entirely build on base load RES, along with a minimum contribution of fossil fuels (in that case as low as 2%), provide substantial cost savings compared to a supply scenario based on solely fossil fuels. Besides, the storage system parameters can be reduced noticeably and the risk of having variable RES jeopardizing the system balance can be limited. Despite the differences in storage size, almost any system that aims to integrate large shares of RES requires are storage system. The major differences are imposed by the services the storage system is expected to cover. While variable RES require the storage system to provide backup over short, medium and long periods, base load RES necessitate a storage system to balance the demand-supply mismatches mainly within the day or over medium periods (i.e. days or up to a week). In either case, pumped hydro storage presents a valuable storage alternative. For islands with limited base load RES availability, it is important to consider several variable RES, mainly because the diversity reduces the demand for storage and, thus, the overall system cost. Due to the limited spatial availability on islands, eventually the focus must shift to offshore RES, which are expected to contribute in larger shares to the future all-purpose electricity supply (confirms first hypotheses).

The proposed research provides powerful and comprehensive insights for energy planning strategies. The great flexibility of the model, in terms of demand development scenarios, RES selection and also in the identification of supply alternatives, allows any applicant or decision makers to incorporate his/her main planning concerns. Besides, all strategies, development trends and solutions can also be compared over time. In the end, it is believed that the proposed energy planning model provides decision makers and energy planners around the world the means to define strategies for future energy systems that are dominated by RES. Subsequently, it is expected that environmental and climate concerns, but also costly import dependencies, can be lowered.

6.2. Future work

Since the energy planning model deals with a great variety of research themes across various scientific areas, there are several aspects that may be considered for future work.

- On the demand side it would be desirable to include the effects of a flexible load and, in this context, an increased contribution of electric vehicles; mainly to assess how much of the load can be declared as flexible and what effects would this have on the overall system cost and the technologies selected.
- The pre-selection process based on site characteristics and resource availability is yet limited in the number of conditions as well as the scoring scale. Further differentiation would be encouraging, especially for the analysis of offshore RETs. The diverse concepts need to be analyzed in more depth, whereby more consideration should be placed on the strengths and weaknesses of each device under certain conditions.
- The MCDA could be improved by applying more sophisticated decision techniques. Yet, it might be even more interesting to apply MCDA only after supply alternatives are identified. Then, the actual capacities of selected RES as well as the overall system cost could be taken into account and the performances of each alternative could be ranked to identify the most preferred one.
- Within the time series algorithm several modifications are encouraging, whereas improvements on the actual selection of the base load limit seem most interesting. In addition, further studies could focus on the interaction of the high RES share, the small fossil fuel contribution and the two storage systems.
- Investigate the reliability of the system under a scenario where electricity is provided mainly by RES. In this regard security of supply and system adequacy may be analyzed as well.
- Investigate new operational procedures for the electricity system given the variability of RES, where forecasting will play a key role in the management of all storage elements.

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A. Appendix A – Review of multi-criteria decision analysis in energy planning

Table A-1: Criteria and sub-criteria for sustainable energy planning using MCDA

	Purpose/aim	Criteria and sub-criteria	Offshore	Storage	# sub-criteria Data type	Multi-criteria decision analysis method
Category: Impact assessment						
Hong et al. [344]	Impact of rural electrification using RET to improve energy access	**T – Ec**: cost, life, power consumed, alternatives consumed **S – Ec**: education level, occupation	N	N	6 M	Multiple corres-pondence analysis [1]
Silva et al. [345]	Assessment of rural electrification with renewable energy systems	**Ec**: electricity generation cost **S**: employment generation **En**: land use, avoided CO_2 emissions	N	N	4 QL	Multi-objective decision making – goal programming
Chatzimouratidis et al [307]	Evaluate impact on the living standard of local communities	**Quality of life**: accident fatalities, non-radioactive emissions, radioactivity, land requirement **S – Ec**: job creation, compensation rates, social acceptance	N	N	7 M	AHP
Heo et al. [346]	Establish criteria for renewable energy dissemination programs	**T**: Superiority of technology, Completeness of technology, Reliability of technology and operation, Possibility of acquiring original technology **Market**: Domestic market size and competitiveness, Global market size and competitiveness, Competitive power of domestic technology **Ec**: Supply capability, Economic feasibility, Supply durability **En**: Reduction of greenhouse gas and pollutants, Requirement of resources, Acceptability of local residents **Policy**: Contribution to achieve dissemination goal, Spillover effect, Linkage with R&D program, Influence of existing social system	N	N	17 QL	Fuzzy AHP
Cherni et al. [347]	Calculate set of appropriate energy options to fulfill local needs	Physical, Financial, Natural, Social, Human	N	N	5 QL	SURE tool
Heano, et al [348]	Selecting energy generation systems for improvement of rural livelihoods	Physical, Financial, Natural, Social, Human	N	N	5 QL	SURE tool
Category: Power generation optimization						
Stein [349]	Rank various renewable and non-renewable electricity production technologies	**Ec**: total overnight cost, variable O&M, fixed O&M, fuel cost; **T**: Production efficiency, capacity factor **En**: External costs, loss of life expectancy **S**: fuel reserve years, job creation, net import as % of consumption	N	N	11 QN	AHP
Ribeiro et al. [350]	Support the evaluation of different electricity production scenarios	**T**: national industry, energy dependency, diversity of mix, rate of dispatchable power **Ec**: costs, investment in transmission network **En**: visual impact, CO_2 emissions, land use **S**: employment, local income, public health, noise	N	N	13 M	Value measurement method; includes impact evaluation, direct weighting and trade-off analysis

Table A-1 continued						
Begic et al. [351]	Multi-criteria sustainability assessment of various options of the energy power system	**Resource**: fuel, carbon steel, stainless steel, copper, aluminum, insulation **En**: CO_2, SO_2, NO_x **Ec**: Energy cost, investment, efficiency **S**: job, diversity	N	N	14 QN	Analysis and synthesis of indexes under deficiency of information (ASPID)
Suo et al. [352]	Select optimal alternative according to their optimism degrees	**T**: energy intensity, retirement, current capacity, potential capacity, service life **Ec**: O&M cost, capital cost **En**: GHG intensity	N	N	8 QN	advanced ordered weighted averaging (AOWA)
Papadopoulos et al. [353]	Optimization of decentralized/ isolated energy systems	**Ec**: NPV, life cycle cost, depreciated payback period, black-out cost **En**: CO_2	N	N	5 QN	ELECTRE III
La Rovere et al. [354]	Analyze the sustainability of the expansion of electricity generation	**T**: Net generation efficiency, average annual availability, construction period, electrical generation potential **Ec**: specific investment, cost-benefit index, percentage of imported inputs **En**: water consumption, specific CO_2 emissions, occupied area, percentage effective land use, specific emissions of non-CO_2 gas emissions **S**: number of direct jobs created, average job income level, job seasonality	N	N	15 M	Data envelope analysis (DEA)
Terrados et al. [355]	Contribute to renewable energies development at regional level	**T**: total primary energy saved, maturity of technology, technical know-how of local actors, continuity and predictability of resources **En**: CO_2, other emissions (SO_2, NO_x), other impacts (noise, visual impact, landscape) **S – Ec**: job creation, financial requirements, compatibility with local, regional and national policies	N	N	11 QN	PROMETHEE
Chatzimouratidis et al. [356]	Evaluation of types of power plant	**T – sustainability**: efficiency coefficient, availability, capacity, reserves/ production (R/P) ratio **Ec**: capital cost, fixed O&M cost, variable O&M cost, fuel cost, external cost	N	N	8 QN	AHP
Van Alphen et al. [357]	Quantification and evaluation of the potentials of available PV and wind	**T**: excess electricity, renewable energy faction **Ec**: capital cost, annual cost, NPV, Levelized cost of energy **En**: emission reduction **S**: fossil fuel savings	N	N	8 QN	Weighted sum (DEFINITE software)
Category: Policy selection						
Kahraman et al. [358]	Select the best energy policy alternative	**T**: feasibility, risk, reliability, duration of preparation phase, duration of implementation phase, continuity and predictability of performance, local technical know how **En**: pollutant emissions, land requirements, need of waste disposal **Ec**: implementation cost, availability of funds, economic value (IRR, cost/benefit) **S**: compatibility with national energy policy objectives, political acceptance, social acceptance, labor impact	N	N	16 QL	Fuzzy AHP
Yi et al. [359]	Solutions to overcome North Koreas chronic energy shortage	**Ec**: facility construction cost, facility maintenance cost, related infrastructure construction cost **Benefit** [S]: availability of energy source within North Korea, area development of North Korea, improvement of inter-Korean relations, development of related industry in South Korea **Risk** [T]: technology transfer problem, appropriateness to North Korea, technological availability and readiness in South Korea	N	N	10 QL	AHP

Table A-1 continued						
Blechinger, et al. [360]	Ascertain preferences for policy measures and instruments	**En**: direct contribution to GHG mitigation, indirect environmental effect **Political acceptability**: cost efficiency, dynamic cost, competiveness, equity, flexibility, stringency for non-compliance **Feasibility of implementation**: implementation network capacity, administrative feasibility, financial feasibility	N	N	10 QL	AHP and Simple Multi-Attribute Rating Technique (SMART)
Category: Scenario evaluation						
Diakoulaki et al. [361]	Examine scenarios for the expansion of electricity system	**T**: guaranteed energy, available power during peak load, security of supply **Ec**: investment cost, production cost **En**: CO_2 increase, SO_2, NO_x	N	N	8 M	PROMETHEE
Georgopoulou et al. [362]	Choose among alternative energy policies at regional level	**T**: safety in covering peak load demand, operationality, stability of the network **Ec**: investment cost, O&M cost **Political**: cohesion to local economic activities, regional employment **En**: air quality, noise, visual amenity, depletion of finite energy sources, risk of climate change, ecosystem´s protection, land use, implementation of EU and national environmental policy	N	N	15 M	ELECTRE III
Category: Technology Selection						
Tsoutsos et al. [30]	Multi-criteria methodology for sustainable energy planning on the island of Crete	**T – Ec**: Investment, O&M cost, conventional fuel savings, maturity of technology, safety of supply **S – En**: CO_2 emissions avoided, contribution to local development and welfare, social acceptance and viability of the remaining environmental effects	N	N	8 M	PROMETHEE
Burton et al. [17]	Comparison of small scale schemes with large-scale alternatives	**T**: generation capacity, lifespan **Ec**: capital cost, O&M cost **En**: CO_2, impact upon natural environment **S**: noise, social effects	N	N	8 M	MACBETH
Afgan et al. [182]	Define energy indicators used in the assessment of energy systems which meet sustainability criterion	**Resource**: Efficiency **En**: Installation cost, electricity cost **Ec**: CO_2 emissions **S**: Area	Y	N	5 QN	Weighted arithmetic mean
Baysal et al. [183]	Selection of renewable energy power plant technologies	**T:** construction period, technical lifetime, capacity factor, maximum availability **Ec:** investment cost, fixed and variable O&M cost, progress ratio	Y	N	7 QL	Fizzy data envelopment analysis (FDEA)
Kaya et al. [363]	1) determining best renewable energy alternative 2) selecting site location	**T**: technical efficiency, exergy efficiency **Ec**: Investment cost, O&M **En**: NO_x emissions, CO_2 emissions, land use **S**: social acceptability, job creation	N	N	9 QL	integrated fuzzy VIKOR [3]-AHP algorithm
Topcu et al. [364]	Selection of suitable electricity generation alternatives	**P**: sustainability of the energy resource, suitability of potential site **En**: Externality cost **Ec**: Levelized cost **Political and uncontrollable**: stability	N	N	5 M	PROMETHEE
Kaldellis et al. [365]	Provide decision makers with tool to evaluate technologies to support power generation	**T**: system efficiency, capacity factor, fuel availability, existing experience **Ec**: 14 criteria, e.g. high paid cost/ton of CO_2, fuel cost, construction cost/long payback period, etc. **En**: 14 criteria, e.g. high gaseous and particulate emissions, hot waste water disposal, microclimate change, etc. **S**: 9 criteria, e.g. noise, accidents, health hazards, people relocation etc.	N	N	41 QL	Delphi method (qualitative evaluating approach)

Table A-1 continued						
Beccali et al. [191]	Diffusion of renewable energy technologies at regional scale	**T**: Targets of primary energy saving in regional scale, Technical maturity & reliability, Consistence of installation and maintenance requirements with local technical know-how, Continuity and predictability of performances, Cost of saved primary energy **Energy and En**: Sustainability according to greenhouse pollutant emissions, Sustainability according to other pollutant emissions, Land requirement, Sustainability according to other environmental impacts **S – Ec**: Labor impact, Market maturity, Compatibility with political, legislative and administrative situation	N	N	13 M	ELECTRE
Afgan et al. [366]	Assessment of hydrogen energy options in comparison with renewables	**Performance**: Efficiency, electricity cost, capital cost, lifetime **Market**: European market, world market **En**: CO_2, NO_x, Kyoto indicator **S**: area, new jobs	N	Y	11 QN	Weighted arithmetic mean
Afgan et al- [367]	Evaluation of hybrid energy systems	**Ec**: Efficiency, electricity cost, investment cost **En**: CO_2 emissions **S**: NO_x emissions	N	Y	5 QN	Weighted arithmetic mean of indicators
Cavallaro et al. [368]	Feasibility assessment to install wind turbines	**T – Ec**: investment cost, O&M cost, energy production capacity, savings of finite energy sources, maturity of technology, realization time **En**: CO_2 emissions avoided, visual impact, acoustic noise, impact on eco-system, social acceptability	N	N	11 M	NAIADE
Evans et al. [369]	Assessment of RETs using sustainability indicators	**T**: Availability and limitations, efficiency **Ec**: Price **En**: CO_2 emissions, land use, water consumption **S**: social impacts	N	N	7 QL	Equal weights
Onat et al. [370]	Assessment of electricity generating technologies	**T**: Availability, efficiency **Ec**: Unit energy cost **En**: CO_2 emissions, land use, fresh water consumpt. S: external costs, external benefits	N	N	8 M	Ranking of criteria and equal weights
Varun et al. [371]	Technology selection for sustainable development	**T**: power rating, life **Ec**: energy pay-back time, cost of electricity generation **En**: GHG emissions	N	N	5 QN	Figure of merit based on equal weighting
Cavallaro [372]	Preliminary assessment of CSP technologies	**T**: maturity of technology, temperature, solar capacity factor **Ec**: investment cost, O&M cost, LEC **En**: environmental impact	N	N	7 M	PROMETHEE, GAIA
Buchholz et al. [373]	Assess sustainability of bioenergy systems with focus on multi-stakeholder inclusion	**Ecological**: reduced competition for fertile land **Ec**: increased local commerce, high cost efficiency, high supply security **S**: low training needs, high employment rate, diversity and certainty in ownership and business schemes, low planning and monitoring needs	N	N	8 QL	AHP, MAUT, PROMETHEE and NAIADE
Pilavachi et al. [374]	Evaluate electrical energy generation options	**T**: efficiency, service of life **En**: CO_2 emissions, NO_x emissions **Ec**: capital cost, O&M costs, electricity cost	N	N	7 QN	AHP
Nigim et al. [375]	Assist communities in prioritizing their RES alternatives	Ecological impact, social and economic benefits, educational potential, Resource availability, technical feasibility, financial feasibility	N	N	6 QL	AHP and SIMUS tool
Erol et al. [376]	Facilitate energy resource planning activities	**T**: possibility of acquiring original technology, superiority of technology, completeness of technology **Ec**: reliability of technology and operation, ease of access to the source, additional investment, source durability, supplementary usage of resources **En**: effect of the technology to the environment, carbon footprint, requirement of resources **Public**: acceptability by local resident	N	N	12 QL	AHP

Table A-1 continued

Streimikiene et al. [377]	Choosing the most sustainable electricity production technologies	**Ec**: private costs, average availability (load) factor, security of supply, costs of grid connection, peal load response **En**: GHG emissions, environmental external costs, radionuclide external cost, human health impact **S**: technology-specific job opportunities, food safety risk, fatal accidents from the past experience, severe accidents perceived in future	N	N	13 M	Multimoora method and TOPSIS
Category: Site selection						
San Cristobal [378]	Selection of a Renewable Energy project	**T**: power, operating hours, implementation period, useful life **Ec**: investment ratio, O&M costs **En**: tons of CO_2 avoided	N	N	7 QN	Compromise ranking method VIKOR
Al-Yahyai et al. [196]	Derive wind farm land suitability index and classification	**T**: wind power density, energy demand matching, percentage of sustainable wind, turbulence intensity, sand dunes **Ec**: distance to road, terrain slope **En**: historical locations, wildlife & natural reserves **S**: urban area	N	N	10 M	Analytical Hierarchy Process with Ordered Weigh Averaging
Defne et al. [198]	Assist in selecting most suitable locations for tidal stream projects	**Physical**: power density **En**: environmental score **S – Ec**: accessibility	Y	N	3 M	GIS and equal weighting
Charabi et al. [197]	Assess the land suitability for large PV farms implementation	**T**: solar radiation, land accessibility, land use **Ec**: grid proximity, land slope, load poles **En**: sensitive areas, hydrographic line, sand/dusk risk	N	N	9 M	Fuzzy Logic Ordered Weighted Averaging (FLOWA)
Haurant et al. [379]	Selection of photovoltaic plant projects	**T**: net production **Geoeconomic**: rent area unoccupied by the installation **Ecological**: study of the potential ecological degradation in the files **En**: relevance of visual impact presentation in the files, observer-plant minimum distance **Territorial use**: use conflicts risks **Ec**: economic activity and inhabitants´ financial benefits related to RES facilities, financial incomes at the communal level	N	N	8 M	ELECTRE
Zhang et al. [380]	Selecting a sustainable energy plan for Nanjing city	**T**: efficiency, safety, reliability **Ec**: investment cost, O&M cost **En**: GHG emissions reduction, land use **S**: job creation, social benefit	N	N	8 QL	Fuzzy integral method
Category: Storage technology selection						
Barin et al. [185]	Evaluate operation of storage energy systems	**T**: efficiency, load management, technical maturity, lifecycle, power quality **Ec**: costs	N	Y	6 M	AHP and fuzzy sets
Raza et al. [186]	Compare different energy storage systems for their sustainability	**T**: fast load response capability, reliability, system life, efficiency, capacity or efficiency variation, risk factor, modularity production, energy density ratio **En**: cost **Ec**: environmental impact	N	Y	10 M	Sustainable Index approach using weighted sum

Abbreviations: N = No; Y = Yes; T = Technical; En = Environmental; Ec = Economic; S = Social; I = Institutional; P = Physical; T – Ec = Techno-economic; S – Ec=Socio-economic; S – En=Socio-environmental
NPV = Net Present Value; O&M = Operation and Maintenance; PP = Payback period; CSP = Concentrated solar power; LEC = Levelized electricity cost
Data type can be quantitative (QN), qualitative (QL) or mixed (M)
1 MCA allows a comparative analysis of categorical data
2 REGIME is a qualitative MCDA method which considers the possibility of partial compensation among different criteria that affect the evaluation of different policy alternatives
3 VIKOR is a simple computation procedure. It allows the simultaneous consideration of the closeness to the ideal or anti-ideal.

Table A-2: Applicability and considered technologies

Ref.	Applied system size and location (Comment)	Onshore						Offshore			Fossil fuels
		S	W	HY	B	G	HG	W	WA	T	
[30]	Regional, Crete	✓	✓		✓						
[17]	Local, small scale, Borough of Kirklees in Yorkshire, UK	✓	✓	✓	✓						✓
[182]	Any – conceptual method	✓	✓	✓	✓	✓	✓				✓
[183]	Technology specific selection	✓	✓	✓		✓		✓			
[191]	Regional, island of Sardinia, Italy	✓	✓	✓	✓						✓
[196]	Local, regional, national, Oman		✓								
[197]	Local, regional, national, Oman	✓									
[198]	Local, regional, coast of Georgia									✓	
[344]	Off-grid, rural, Pangan-an Island, Philippines	✓									
[307]	Local community level up to national level	✓	✓	✓	✓	✓					✓
[346]	National, Korea										
[345]	Remote areas, rural, non-interconnected zones Columbia	✓	✓	✓	✓						✓
[347]	Rural livelihoods, communities, San Jose, Colombia	✓		✓	✓						✓
[348]	Rural livelihoods, communities, Jambaló, Colombia	✓		✓	✓						✓
[349]	Any - Power system optimization tool	✓	✓	✓	✓	✓					✓
[350]	Large, national, Portugal		✓	✓							✓
[351]	Regional to national - Bosnia	✓	✓	✓	✓						✓
[353]	Remote region, isolated Greek islands Karpathos and Kassos	✓	✓		✓						
[354]	Any – conceptual method		✓	✓	✓						
[352]	Local, regional, power stations		✓	✓	✓						✓
[355]	Local, regional, Province Jaen, Spain	✓	✓	✓	✓						✓
[356]	Local, regional to national	✓	✓	✓	✓	✓					✓
[357]	Local, regional, city, islands, Male, Maldives	✓	✓								
[358]	National, Turkey	✓	✓	✓	✓	✓					
[359]	National, North Korea	✓	✓	✓	✓	✓					✓
[360]	Regional, national policies, Trinidad and Tobago										
[361]	National, Greece		✓	✓							✓
[362]	Local, regional level, Crete	✓	✓		✓						✓
[381]	Regional, Thassos, Greece	✓	✓	✓	✓	✓					
[364]	Regional to national, Turkey	✓	✓	✓	✓						✓
[365]	Regional and National, Crete and Greece	✓	✓								✓
[363]	Local, city, Istanbul	✓	✓	✓	✓	✓					
[366]	Any – conceptual method	✓	✓				✓				✓
[367]	Any – conceptual method	✓	✓		✓		✓				✓
[368]	Local to regional, island of Salina, Italy		✓								
[369]	Any – conceptual method	✓	✓	✓		✓					
[370]	Any – conceptual method	✓	✓	✓		✓	✓				✓
[371]	International/National	✓	✓	✓							
[372]	Technology specific selection	✓									
[373]	Local, regional, national, Uganda				✓						✓
[374]	Technology specific selection						✓				✓
[375]	Local, communities, Waterloo Region, southern Ontario	✓	✓	✓		✓					
[376]	Local, regional, district of Aydin, Turkey	✓	✓	✓		✓					✓
[377]	Technology specific selection	✓	✓	✓	✓						✓
[379]	Local, regional, Corsica Island	✓									
[380]	Local, city-level, Nanjing, China	✓			✓	✓					
Total (46)		35	33	27	25	14	5	1	0	1	24
S = Solar; W = Wind; HY = Hydro; HG = Hydrogen; G = Geothermal; B = Biomass; WA = Wave; T = Tidal; [✓] = yes											

B. Appendix B – Energy flowchart

Due to the lack of precise data for all energy flows on the Azores at the time of the conduction of this chart, a sample of a flowchart is created (Figure B-1) with data of the EU-27. The EU-27 was selected since it provides comprehensive data and information about all energy flows. The methods to create the flowchart can be applied to any other closed system if adequate data is available. The more assumptions that are required the more inaccurate the flowchart becomes. For any user of this model the herein presented procedures to create the flowchart can be used as a benchmark. Nonetheless, several aspects reflecting the actual conditions of the analyzed case have to be considered. This is includes aspects such as local resource and climate conditions, behavioral habits, political concepts and so forth. It is suggested to use energy consumption pattern of the country of which the energy system shall be analyzed or of a country with similar conditions, for instance the breakdown of residential energy consumption in Spain if no data for Portugal is available.

Based on the data provided in literature and statistical databases, all energy flows from their primary source to their end-use (useful energy) are analyzed [382], [383], [384], [385]. Minor assumptions were required to establish the flowchart (See notes Figure B-1). Its detailed classification of energy vectors and services can be a benchmark in the scenario building, especially if breakdowns at the final and useful energy level are lacking data.

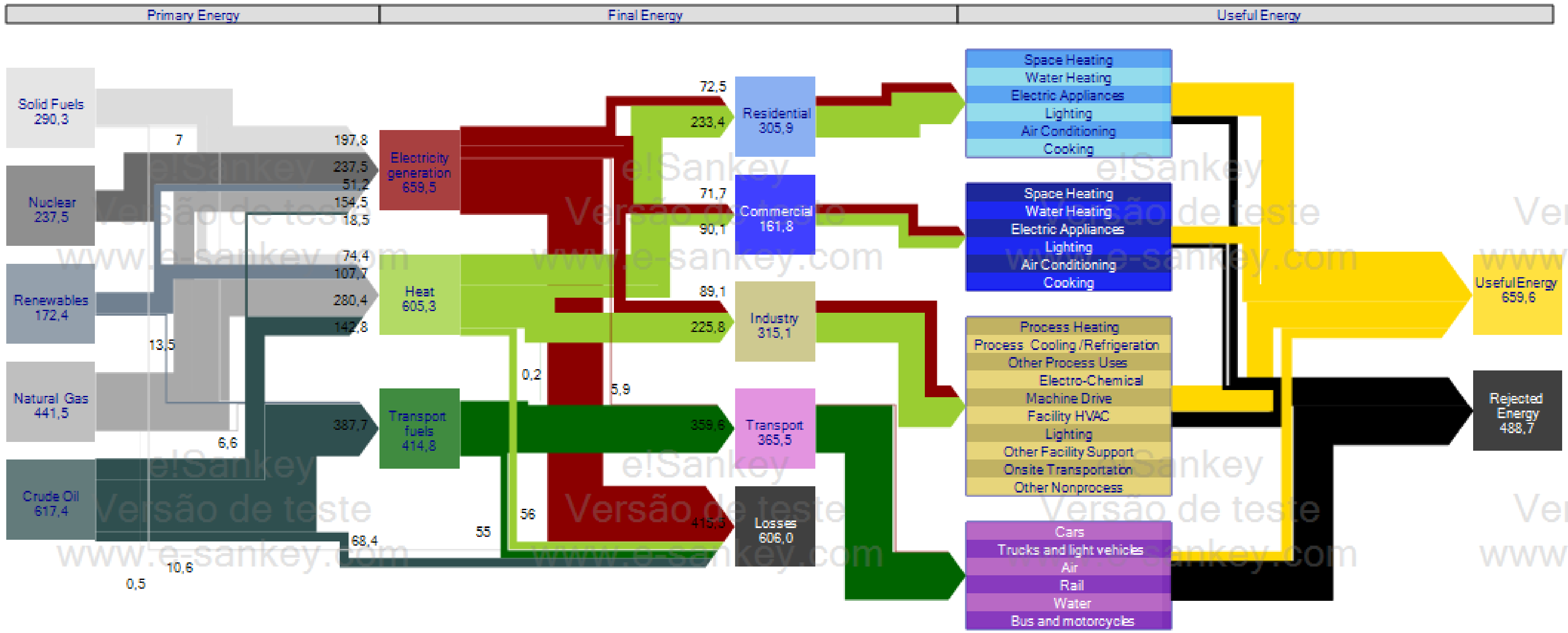


Figure B-1: Energy flowchart EU-27 (adapted based on [386])

Notes:
- 0.6% of non-renewable waste was considered in solid fuels of primary energy consumption
- Electricity: 2% go in other than the proper service sector; this includes own-energy use (industry)
- 3% crude oil goes into electricity generation
- Small adjustment was needed for heat. 4.8 Mtoe were reduced according to the share of households, services and industry (-2 mtoe for households, -0.8 mtoe for services and -2 for industry)
- Cars represent road passenger transport and trucks and light vehicles are the road freight transport

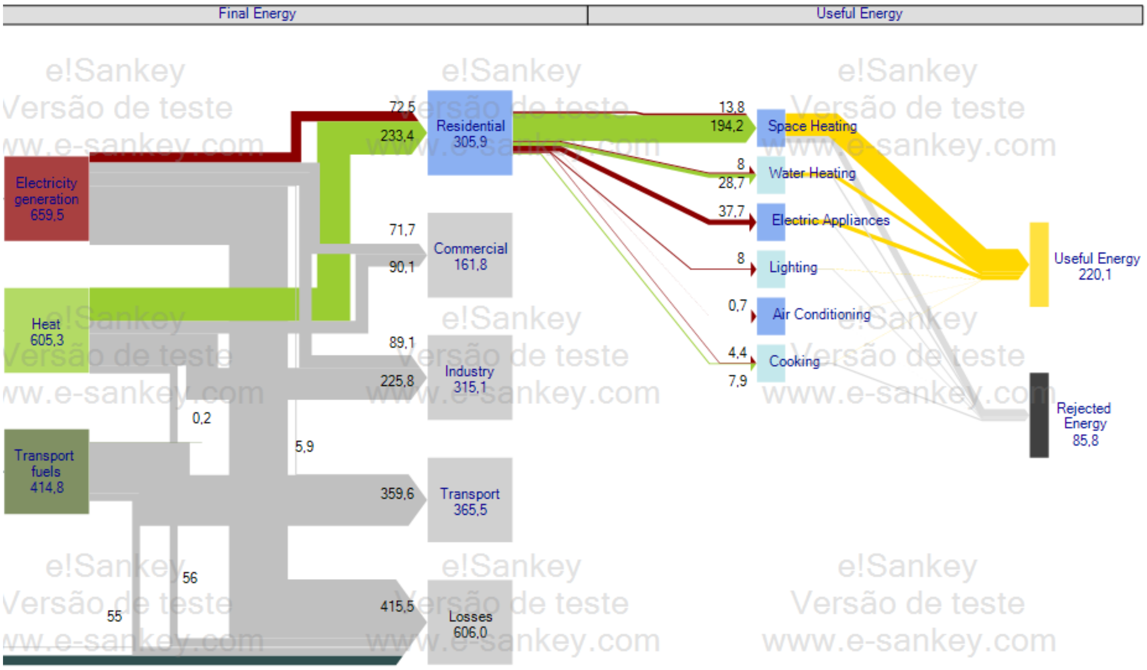


Figure B-2: EU-27 useful energy service breakdown for the residential sector

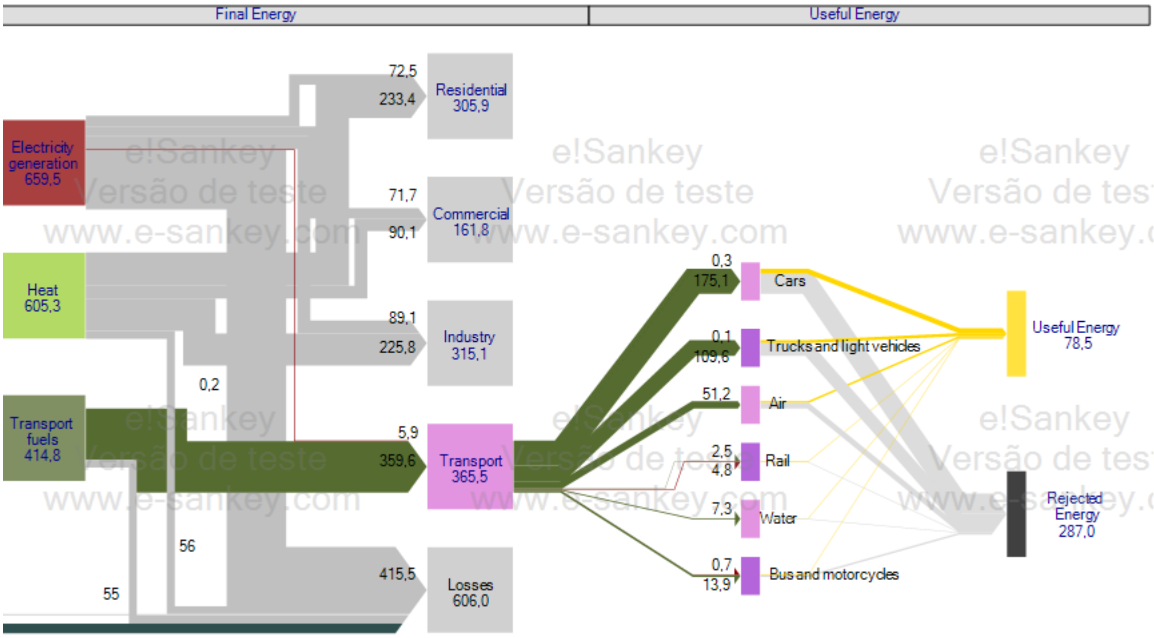


Figure B-3: EU-27 useful energy service breakdown for the transport sector

C. Appendix C – Offshore RET companies contacted for survey

Table C-1: Tidal energy companies and contacts

	Technology/name	Manufacturers	Website	Contacts
Horizontal axis	Clean Current	Clean Current	http://www.cleancurrent.com/	info@cleancurrent.com
	Contra-Rotating Marine Turbine (CoRMaT)	University of Strathclyde / Nautricity	http://www.nautricity.com/cormat/	florence.harvester@nautricity.com
	DEEP-Gen	Tidal Generation Ltd.	http://www.alstom.com/products-services/product-catalogue/power-generation/renewable-energy/ocean-energy/tidal-energy/tidal-power/	http://www.alstom.com/grid/contact-us/
	DeltaStream	Tidal Energy	http://www.tidalenergyltd.com/?page_id=21	info@tidalenergyltd.com
	DeltaStream	Marine Energy Pembrokeshire	http://www.marineenergypembrokeshire.co.uk/	pcf@mhpa.co.uk
	Evopod (North Shields)	Oceanflow Energy	http://www.oceanflowenergy.com/	info@oceanflowenergy.com
	Free Flow Kinetic Hydropower System	Verdant Power	http://verdantpower.com/what-systemsint/	http://verdantpower.com/contact-general/
	Hammerfest Strom AS	Andritz hydro hammerfest	http://www.hammerfeststrom.com/	contact@hammerfeststrom.com
	Hydra Tidal	Straum	http://www.straumgroup.com/hydratidal	mail@straumgroup.com
	Hydro+	Hydro Green Energy	http://hgenergy.com/index.php	mike@hgenergy.com
	HydroCoil	HydroCoil Power Inc.	http://www.hydrocoilpower.com/	rich@hydrocoil.com
	Nereus	Atlantis Resources Corportation	http://atlantisresourcesltd.com/	http://atlantisresourcesltd.com/contact-us-161/general-enquiries.html
	Open-Centre Turbine	OpenHydro	http://www.openhydro.com/home.html	info@openhydro.com
	ORPC Turbine Generating Unit	Ocean Renewable Power Company	http://www.orpc.co/orpcpowersystem_turbinegeneratorunit.aspx	info@orpc.co
	Osprey	Free Flow 69	http://www.freeflow69.com/	sales@freeflow69.com
	RED HAWK Tidal Turbine	Natural Currents Energy Services	http://www.naturalcurrents.com/partners/	rbason@naturalcurrents.com
	Rotech Tidal Turbine	Lunar Energy	http://www.lunarenergy.co.uk/index.htm	andrea.tyrrell@lunarenergy.co.uk
	Sabella D03	Sabella	http://www.sabella.fr/cat.php?id=3&lg	contact@sabella.fr
	Scotrenewables Tidal Turbine	Scotrenewables Tidal Power Ltd	http://www.scotrenewables.com/	calum@scotrenewables.com
	SeaGen	Marine current technology	http://www.marineturbines.com/Seagen-Technology	info-mct.energy@siemens.com
	SeaUrchin	Elemental Energy Technologies Ltd.	http://eetmarine.com/	info@eetmarine.com
	SmarTurbine Generator	Free Flow Power	http://www.free-flow-power.com/home	info@free-flow-power.com
	Swan turbine	Swanturbines	http://www.swanturbines.co.uk/	james.orme@swanturbines.co.uk
	Tidal Star	Bourne Energy	http://www.bourneenergy.com/	contact@bourneenergy.com

Table C-1 continued

	TidEl	SMD Hydrovision	http://www.tidalenergy.eu/smdhydrovision_tidel.html	mike.jones@smd.co.uk
	Tocardo	Teamwork Technology (Tocardo Tidal Energy Ltd.)	http://teamwork.nl/en	http://teamwork.nl/en/contact-teamwork
	Triton 6	TidalStream	http://www.tidalstream.co.uk/	info@tidalstream.co.uk
	Underwater Electric Kite Low Impact Hydrokinetic Turbine	UEK Corporation	http://www.uekus.com/	http://www.uekus.com/contact.html
Vertical axis	Atlantisstrom	Atlantisstrom	http://www.atlantisstrom.de/	info@atlantisstrom.de
	Cycloidal turbine	QinetiQ	http://www.qinetiq.com/Pages/default.aspx	http://www.qinetiq.com/contact/Pages/enquiry.aspx
	Davis Hydro Turbine	Blue Energy	http://www.bluenergy.com/about/company/	http://www.bluenergy.com/contact/
	EnCurrent Turbine	New Energy Corporation	http://www.newenergycorp.ca/	info@newenergycorp.ca
	Gorlov turbine	GCK Technology	http://www.gcktechnology.com/GCK/pg2.html	kurth@gcktechnology.com
	Kobold turbine	Sino-Italian Cooperation Program	http://www.sinoitaenvironment.org/indexe02.asp	info@sinoitaenvironment.org
	Neptune proteus tidal power pontoon	Neptune Renewable Energy	http://technology4sme.net/TechOffer/TechOfferDetail.aspx?OffId=714	jackhardisty@neptunerenewableenergy.com
	Pulsus turbine	Norwegian Ocean Power	https://www.norwegianoceanpower.com/	kt@norwegianoceanpower.com
	Sea Power International AB	EXIM	http://www.seapower.se/	http://www.seapower.se/contact.aspx
	Sundermann Turbine	Sundermann Water Power Limited	http://www.sundermannwaterpower.com/	leigh.bennett@sundermannwaterpower.com
	Wave Rotor	C-Energy	http://www.ihctidalenergy.com/projects/	http://www.ihctidalenergy.com/rightmenu/contact/
	WWTurbine	Water Wall Turbine	http://www.wwturbine.com/	info@wwturbine.com
Hydrofoil	AES sails	Aqua Energy Solutions	http://www.aquaenergy.no/technology/	janchristian@aquaenergy.no
	bioStream	BioPower Systems	http://www.sba.asn.au/sba/mp-biopower.asp	info@biopowersystems.com
	Deep Green	Minesto	http://www.minesto.com/index.html	anders.jansson@minesto.com
	Harmonica (Triangular tidal sails)	Tidal Sails AS	http://tidalsails.com/	are@tidalsails.com
	Oscillating Hydrofoil	Laval University	http://www.hydrolienne.fsg.ulaval.ca/en/home/	
	Pulse Generator	Pulse Tidal	http://www.pulsetidal.com/	howard.nimmo@pulsetidal.com
	SeaSnail	Robert Gordon University	http://www4.rgu.ac.uk/cree/general/page.cfm?pge=10769	p.pollard@rgu.ac.uk /
	Stingray	Engineering Business Ltd.	http://www.engb.com/	ebl@ihcmerwede.com
	Vortex induced vibration	VIVACE	http://www.vortexhydroenergy.com/	michaelb@umich.edu
Venturi	Davidson-Hill Venturi Turbine	Tidal Energy Pty. Ltd.	http://www.tidalenergy.net.au/	aaron@tidalenergy.com.au
	Gentec Venturi	Greenheat Systems Limited	http://www.greenheating.com/	solutions@greenheating.com
	Hydro Venturi	Hydro Venturi Ltd.	http://www.hydroventuri.com/	info@hydroventuri.com
Total	**52**			

Note: All listed companies were identified by the beginning of 2014.

Table C-2: Wave energy companies and contacts

	Technology/name	Manufacturers	Website	Contacts
Attenuator	Squid	AlbaTERN	http://albatern.co.uk/	info@albatern.co.uk
	DEXAWAVE converter	DEXAWAVE A/S	http://www.dexawave.com/	info@dexawave.com
	Centipod	Ecomerit Technologies	http://www.ecomerittech.com/centipod.php	info@ecomerittech.com
	Poseidon – Wave wind hybrid	Floating Power Plant AS	http://www.floatingpowerplant.com/?pageid=336	info@floatingpowerplant.com
	The B1 Buoy	Fred Olsen Ltd	http://www.fredolsen.com/	press@fredolsen.co.uk
	Syphon Wave Generator	Gedward Cook	-	-
	Wave Turbine	Greencat Renewables	http://www.greencatrenewables.co.uk/	info@greencatrenewables.co.uk
	Free Floating Wave Energy Converter (FFWEC)	Group Captain SM Ghouse	http://www.linkedin.com/pub/gp-capt-sm-ghouse-retd/2b/19/5a2	-
	Wave Energy Propulsion	Kneider Innovations	http://kneider.voila.net/	-
	FLOW	Martifer Energia	http://www.martifer.pt/pt/	info@martifer.com
	Navatek WEC	Navatek Ltd	http://www.navatekltd.com/waveenergy.html	eric@NavatekLtd.com
	Oceantech Energy Convertor	Oceantec Energias Marinas SL	http://www.oceantecenergy.com/	info@oceantecenergy.com
	Pelamis	Pelamis Wave Power	http://www.pelamiswave.com/	enquiries@pelamiswave.com
	Hybrid Float	PerpetuWave Power Pty Ltd	http://www.perpetuwavepower.com/	info@perpetuwavepower.com
	Pontoon Power Converter	Pontoon Power	http://www.pontoon.no/	nm@pontoon.no
	Sea Power Platform	Sea Power Ltd	http://www.seapower.ie/	info@seapower.ie
	PSE-MAR	Tecnalia	http://www.energiasmarinas.es/cas/noticias.aspx	energia@tecnalia.com
	Salter´s Duck	University of Edinburgh	http://www.mech.ed.ac.uk/research/wavepower/	ies.contact@eng.ed.ac.uk
	Vigor Wave Energy Convertor	Vigor Wave Energy AB	http://www.vigorwaveenergy.com/	daniel.ehrnberg@vigorwaveenergy.com
	Vortex Oscillation Technology	Vortex Oscillation Technology Ltd	http://www.vortexosc.com/index.php?newlang=english	esorokodum@dol.ru
	Waveberg	Waveberg Development	http://www.waveberg.com/	pwegener@waveberg.com
	WavePiston	WavePiston	http://www.wavepiston.dk/	phc@wavepiston.dk
	Duck	Ocean Energy Laboratory of Guangzhou	http://www.giec.ac.cn/	youyg@ms.giec.ac.cn
	Eagle	Ocean Energy Laboratory of Guangzhou	http://www.giec.ac.cn/	youyg@ms.giec.ac.cn
	Crestwing	Waveenergyfyn (Crestwing)	http://crestwing.dk/	crestwing@gmail.com
	StingRAY	Columbia Power Technologies	http://columbiapwr.com/	info@columbiapwr.com
	Rock n Roll wave energy device	Nualgi Nanobiotech	http://rocknroll.nualgi.com/	sampath@nualgi.com
Point absorber	Electric Generating Wave Pipe	Able Technologies LLC	http://www.abletechnologiesllc.com/	srutta@yahoo.com
	Eel Grass	Aero Vironment Inc	-	-
	Float Wave Electric Power Station	Applied Technologies Company Ltd	http://atecom.ru/	atecom@atecom.ru
	Electric Buoy	Aqua-Magnetics Inc	http://www.amioanpower.com/home	-

Table C-2 continued

	OHS Wave Energy Array	Ocean Hydropower Systems Ltd	http://www.oceanhydropowersystems.com/	ohs.kithil@gmail.com
	TWPEG	Balkee Tide and Wave Electricity Generator	-	-
	Blue Power Energy	Blue Power Energy Ltd	http://www.bluepower.ie/	damien.browne@bluepower.ie
	Brandl Generator	Brandl Motor	http://brandlmotor.de/index_eng.htm	info@brandlmotor.com
	CETO	Carnegie Wave Energy Ltd	http://www.carnegiewave.com/	enquiries@carnegiewave.com
	CPO2	CorPower Ocean AB	http://www.corpowerocean.com/	info@corpowerocean.com
	Delbuoy Wave Powered Desalination	Delbuoy	http://www.solutions-site.org/node/82	dhicks@college.dtcc.edu
	Searaser	Ecotricity	http://www.ecotricity.co.uk/our-green-energy/our- green-electricity/and-the-sea/seamills	home@ecotricity.co.uk
	Horizon Platform	ELGEN Wave	http://www.elgenwave.com/	info@elgenwave.com
	Euro Wave Energy	Euro Wave Energy	http://www.eurowaveenergy.com/	olaf@eurowaveenergy.com
	Rho-Cee	Float Inc	http://www.floatinc.org/	projects1@floatinc.com
	SEEWEC	Fred Olson & Co./Ghent University	http://www02.abb.com/global/gad/gad02077.nsf/lupLongContent/D74F5739AAE738F6C12571D800305007	albert.leirbukt@no.abb.com
	Drakoo	Hann-Ocean	http://www.hann-ocean.com/	http://www.hann-ocean.com/contact-us/
	Hidroflot	HidroFlot SA	http://www.hidroflot.com/en/index.php	info@hidroflot.com
	Seacap	Hydrocap Energy SAS	http://www.hydrocap.com/	info@hydrocap.com
	SEADOG	Independent Natural Resources	http://www.inri.us/	seadog@inri.us
	IWAVE	India Wave Energy Device	http://waveenergy.nualgi.com/	sampath@nualgi.com
	TETRON	Joules Energy Efficiency Services Ltd	-	-
	PS Frog	Lancester University	http://www.engineering.lancs.ac.uk/lureg/group_research/wave_energy_research/	r.chaplin@lancaster.ac.uk
	Motor Wave	Motor Wave	http://www.motorwavegroup.com/new/index1.html	gambarota@motorwavegroup.com
	CONWEC	Norwegian University of Science and Technology	-	-
	WaveSurfer	Ocean Energy Industries Inc	http://www.oceanenergyindustries.com/	info@oceanenergyindustries.com
	Ocean Harvester	Ocean Harvesting Technologies	http://www.oceanharvesting.com/	mikael.sidenmark@oceanharvesting.com
	OMI Combined Energy System	Ocean Motion International	http://www.oceanmotion.ws/	http://oceanmotionintl.com/
	Power Buoy	Ocean Power Technologies	http://www.oceanpowertechnologies.com/	info@oceanpowertech.com
	OWEC Ocean Wave Energy Converter	OWEC Ocean Wave Energy Company	http://www.owec.com/	foerd@owec.com
	SeaHeart	Oceanic Power	http://www.oceanicpower.com/empresa/	info@oceanicpower.com
	W2Power	Pelagic Power AS	http://www.pelagicpower.no/	post@pelagicpower.no
	Protean	Protean Energy Limited	http://www.proteanenergy.com/	-
	The "Fisherman" WEC	Purneco AS	http://www.straumekraft.no/	-

Table C-2 continued

	Renewable Energy Pumps	Renewable Energy Pumps	http://www.renewableenergypumps.com/	hjk5607@yahoo.co.kr
	Linear generator (Islandberg project)	Seabased AB	http://www.seabased.com/	info@seabased.com
	Seatricity	Seatricity	http://www.seatricity.net/	enquiries@seatricity.net
	Surfpower	Seawood Designs Inc	http://www.surfpower.ca/	seawood@shaw.ca
	FO3	SEEWEC Consortium	http://www.seewec.org/consortium.html	-
	Snapper	Snapper Consortium	http://www.snapperfp7.eu/home	Stephen.Robertson@narec.co.uk
	nPower WEC	Tremont Electric	http://www.npowerpeg.com/	info@nPowerPE
	PowerPod	Trident Energy Ltd	http://www.tridentenergy.co.uk/our-technology/	info@tridentenergy.co.uk
	WET EnGen	Wave Energy Technologies Inc	http://www.waveenergytech.com/	info@waveenergytechnologies.com
	WET-NZ device	Wave Energy Technologies New Zealand	http://www.wavenergy.co.nz/	enquiries@powerprojects.co.nz
	Wave Star	Wave Star Energy ApS	http://wavestarenergy.com/	info@wavestarenergy.com
	WaveBob	WaveBob Limited	http://www.wavebob.com	-
	WaveEL-buoy	Waves 4 Power	http://www.waves4power.com/	ulf.lindelof@waves4power.com
	WaveSub	Marine Power Systems	http://marinepowersystems.co.uk/	contact@marinepowersystems.co.uk
	Spindrift Energy Device	Spindrift Energy	http://www.spindriftenergy.com/	moffatbrian@gmail.com
	Wave Pump Rig	Ocean Wave and Wind Energy	http://www.owwe.net/	http://www.owwe.net/?o=contact
	Neza II	Ocean Energy Laboratory of Guangzhou	http://www.giec.ac.cn/	youyg@ms.giec.ac.cn
	SurgeDrive	Aquagen Technologies	http://www.aquagen.com.au/	info@aquagen.com.au
	Wave platform	Ocean Electric Inc	http://ocel.com/	http://ocel.com/contact/
	Sperboy	Embley Energy Limited	http://www.sperboy.com/flashes/intro.html	info@sperboy.com
	Resen Waves LOPF buoys	RESEN ENERGY	http://www.resenwaves.com/	info@resenwaves.com
	Wave Catcher	Marine Energy Corporation	http://www.marineenergycorp.com/	sales@marineenergycorp.com
Oscillating Wave Surge Converter	Oyster 800	Aqumarine Power	http://www.aquamarinepower.com/	info@aquamarinepower.com
	WaveRoller	AW Energy	http://aw-energy.com/	info@aw-energy.com
	Wave Energy Conversion Activator	Daedalus Informatics Ltd	http://www.daedalus.gr/	info@daedalus.gr
	Langlee System	Langlee Wave Power	http://www.langleewavepower.com/	post@langleewavepower.com
	OWEL WEC	Offshore Wave Energy Ltd	http://www.owel.co.uk/owel-technology/	nminns@owel.co.uk
	SurgeWEC	Resolute Marine Energy Inc	http://www.resolutemarine.com/	contactus@resolutemarine.com
	SDE	SDE	http://www.sde.co.il/	-
	Yu Oscillating Generator	Yu Energy Corp	http://www.yuenergy.com/	Contact@YuEnergy.com
	Volta WaveFlex	Polygen Ltd	http://www.polygenlimited.com/	reavis@polygenlimited.com
	Ocean WaveFlex	Polygen Ltd	http://www.polygenlimited.com/	reavis@polygenlimited.com
	bioWave	BioPower Systems Pty Ltd	http://www.biopowersystems.com/	http://www.biopowersystems.com/contact-us.html

Table C-2 continued

Oscillating water column	SEAREV	Ecole Centrale de Nantes	http://www.bulletins-electroniques.com/actualites/52074.htm	hakim.mouslim@ec-nantes.fr
	FO3	Fobox AS	http://www.orecca.eu/consortium/fobox	post@fredolsen.no
	Titan Platform	Grays Harbor Ocean Energy Company	http://www.graysharboroceanenergy.com/technology.htm	-
	Multi-Absorbing Wave Energy Converter	Leancon Wave Energy	http://www.leancon.com/	kdr@leancon.dk
	Ocean Energy Buoy	Ocean Energy Ltd	http://www.oceanenergy.ie/	info@oceanenergy.ie
	greenWAVE	Oceanlinx	http://www.oceanlinx.com/	info@oceanlinx.com
	OWC	GasNatural Fenosa	http://www.gasnaturalfenosa.com/en/1285338501612/home.html	-
	Limpet	Votih Hydro Wavegen	http://voith.com/en/products-services/hydro-power/ocean-energies/wave-power-plants-590.html	-
	Pico Plant	Wave Energy Centre (WavEC)	http://www.wavec.org/en	mail@wavec.org
	OWC Plant	OWC Power AS	http://www.straumgroup.com/	mail@straumgroup.com
	ogWave	Oceanlinx	http://www.oceanlinx.com/	info@oceanlinx.com
	blueWAVE	Oceanlinx	http://www.oceanlinx.com/	info@oceanlinx.com
	OWC Power	Straum	http://www.straumgroup.com/owcpower	anders.torud@straumgroup.com
	Evolver	Havkraft	http://www.havkraft.no/	geir@havkraft.no
Overtopping/ Terminator device	AWS III	AWS Ocean Energy	http://www.awsocean.com/PageProducer.aspx	nicky.stainke@awsocean.com
	WaveTORK	Inerjy	http://www.inerjy.com/Products.htm	http://www.inerjy.com/ContactUs.htm
	Mighty Whale	JAMSTEC	http://www.jamstec.go.jp/jamstec-e/30th/part6/page2.html	-
	PowerGin	Kinetic Wave Power	http://www.kineticwavepower.com/	info@kineticwavepower.com
	OWWE-Rig	Ocean Wave and Wind Energy	http://www.owwe.net/	http://www.owwe.net/?o=contact
	WAVESTORE	Portsmouth Innovation Limited	http://homepage.ntlworld.com/b.spilman/index.htm	b.spilman@ntlworld.com
	Wave Dragon	Wave Dragon	http://www.wavedragon.net/	info@wavedragon.net
	Seawave Slot-Cone Generator	Wave Energy AS	http://www.waveenergy.no/	- "back soon"
	WavePlane	WavePlane Production	http://www.waveplane.com/	es@asolutioninvent.com
Submerged pressure differential	SARAH Pump	College of the North Atlantic	http://www.cna.nl.ca/news/newsletters/Fall%202006.pdf	mike.graham@cna.nl.ca
	DMP Device	M3 Wave LLC	http://m3wave.com/default.htm	info@m3wave.com
	Turbo Outburst Power/Top Desalination System	SeaNergy	http://www.seanergy.co.il/	http://www.seanergy.co.il/#! page-1
	Bombora	Bombora Wave Power	http://www.bomborawavepower.com.au/	shawn.ryan@bomborawavepower.com.au
	Floating Wave Generator	Gedward Cook	http://www.gedwardcook.com/	-
Bulge wave	Anaconda	Checkmate Seaenergy UK Ltd	http://www.checkmateukseaenergy.com/	des@checkmateuk.com
Rotating mass	Penguin	Wello OY	http://www.wello.eu/	info@wello.eu
	WE 10/WE 50/WE 125	WavElectric Inc	http://www.wavelectric.com/	afm@waveelectric.com
Others	Lifesaver	BOLT (Fred Olson)	http://www.boltwavepower.com/	press@fredolsen.co.uk
	DUO Wave Energy Converter	Pure Marine	http://www.puremarinegen.com/	info@puremarinegen.com

Table C-2 continued

	MD wave power converting device	Sigma Energy	http://www.sigma-energy.si/index.php?p=3_1	info@sigma-energy.eu
	Wavecat	Norvento	http://www.norvento.com/contenido.asp?m=77	http://www.norvento.com/contacto.asp
	APC-PISYS	PIPO Systems	http://www.piposystems.com/sistemaapspisys.html	info@piposystems.com
	RTI Ocean Wave Energy Converter	RTI Ocean Wave Energy	http://futureenergy.ultralightstartups.com/campaign/detail/946	-
	R115	40South Energy	http://www.40southenergy.com/	info@40southenergy.com
	Wave Pioneer	FlanSea	http://www.flansea.eu/	-
	Energy Island	Marine Power Technologies Pty Ltd	http://mptenergy.com/	info@mptenergy.com
	iMEC	Oscilla Power	http://oscillapower.com/	http://oscillapower.com/contact-us/
	Yeti Cluster System	Avium AS	http://avium.com.tr/	wec@avium.com.tr
	Wave Plane	Caley Ocean Systems	http://caley.co.uk/	info@caley.co.uk
	Wave Rotor	IHC Tidal Energy	http://www.ihctidalenergy.com/	tidalenergy@ihcmerwede.com
	Power Wing	Eco Wave Power	http://www.ecowavepower.com/	info@ecowavepower.com
	Gentec WaTS	Greenheat Systems Ltd	http://www.greenheating.com/	solutions@greenheating.com
	GyroWaveGen	GyroWaveGen	-	-
	Intentium Offshore Wave Energy Converter	Intentium AS	http://www.intentium.com/	lars.edvardsen@intentium.com
	Intentium short-crest Wave Energy Converter	Intentium AS	http://www.intentium.com/	lars.edvardsen@intentium.com
	Irish Tube Compressor	Jospa Ltd	http://www.jospa.ie/	info@jospa.ie
	Pendulor	Muroran Institute of Technology	http://www.muroran-it.ac.jp/en/	-
	Nodding Beam	Nodding Beam	http://www.noddingbeam.com/	info@noddingbeam.com
	MHD Wave Energy Conversion	SARA Inc	http://www.sara.com/RAE/ocean_wave.html	sara.forms@gmail.com
	WEPTOS WEC	Weptos	http://www.weptos.com/	weptos@weptos.com
	Wave Blanket	Wind Waves and Sun	http://www.windwavesandsun.com/welcome.htm	Ben@WindWavesandSun.com
	Solar Marine Cells	PAULEY	http://www.philpauley.co.uk/	info@pauley.co.uk
	Cycloidal Wave Energy Converter	Atargis Energy Corporation	http://www.atargis.com/	http://www.atargis.com/Contact_Us.php
	Ocean 3	Ocean RusEnergy	http://oceanrusenergy.com/	info@oceanrusenergy.com
	Waveline Magnet	Sea Wave Energy Ltd	http://www.swel.eu/	adam.zakheos@swel.eu
	Wave Clapper	Eco Wave Power	http://www.ecowavepower.com/	info@ecowavepower.com
	Ocean 640	Ocean RusEnergy	http://oceanrusenergy.com/	info@oceanrusenergy.com
	Ocean 160	Ocean RusEnergy	http://oceanrusenergy.com/	info@oceanrusenergy.com
	Etymol WEC - Alfa Series	Etymol Ocean Power SpA	http://www.etymol.com/	contacto@etymol.com
Total	**155**			

Note: All listed companies were identified by the beginning of 2014.

D.Appendix D – Development trends and expected changes of the alternative´s attribute values over time

Table D-1: Development trends and expected indicator changes for bioenergy

Indicator	Development trends/expected indicator changes over time
CF	- No change over time expected
REL	- Minor increases over time for all bioenergy technology types were performed - For technologies with values already above 90% only 1% point was increased per decade; mainly on lower range - Fluidized bed gasifiers remained unchanged - For technologies with lower values in the range of 70-80% moderate increases in the range of 2-5% points per decade were undertaken; always with a greater increase on the lower range
IC	- Minor to significant reductions expected [387] - 10% reduction per decade on higher range for all technologies except pyrolysis - 5% reduction per decade on higher range for pyrolysis - No reduction on lower range for stoke boiler, fluidized bed boiler, CHP and pyrolysis - 5% reduction on per decade on lower range for fixed bed, fluidized bed and entrained flow gasifiers and anaerobic digestion
O&MC	- Minor/considerable reduction over time expected [315] - 2% reduction per decade on lower range - 5% reduction per decade on higher range
LT	- No change over time expected
$LCCO_2E$	- Minor reduction over time is expected - But only on higher range; low range remains unchanged - 2% reduction per decade on higher range of $LCCO_2E$
LU	- Reductions are foreseen due to technology development - 5% reduction potential per decade on land use - Reductions are based on rounded values
JC	- No change over time expected except for pyrolysis and anaerobic digestion (5% per decade)
PA	- No change over time expected

Table D-2: Development trends and expected indicator changes for solar energy

Indicator	Development trends/expected indicator changes over time
CF	- Minor increase for all solar PV cells over time - Efficiency increase leads to higher CF - 1% point increase over time for emerging cells and thin-film - 2% point increase over time for single junction GaAs and crystalline cells - 3% point increase over time for multi-junction cells - Minor increase for parabolic trough of 1% score per decade up from 2 second decade [291], [388], [389], [390]
REL	- Minor increase for PV cells (1% score per decade on lower range) - Minor increase for parabolic trough of 2% score each decade up to 98% [291]
IC	- Significant cost reduction for solar photovoltaic cells [391] - 40% reduction in first decade, 30% reduction in second decade, 20% reduction in third decade - Significant cost reduction for parabolic trough [392] - 10% reduction per decade on lower range - 20% reduction per decade on higher range
O&MC	- Significant reduction over time expected for all solar photovoltaic cells - 10% reduction per decade on lower range - 20% reduction per decade on higher range - Considerable reduction over time is expected for parabolic trough [291], [392] - 5% reduction per decade on lower and higher range of parabolic trough
LT	- No change over time expected
$LCCO_2E$	- Minor reduction over time expected - 1% reduction per decade on lower range of $LCCO_2E$ - 2% reduction per decade on higher range of $LCCO_2E$
LU	- Minor/considerable reduction over time expected - 1% reduction per decade on lower range of $LCCO_2E$ for all including parabolic trough - 5% reduction per decade on higher range of $LCCO_2E$
JC	- Minor reduction expected over time; except for parabolic trough which remains unchanged - 5% reduction potential per decade on land use for remaining solar technology choices
PA	- No change over time expected

Table D-3: Development trends and expected indicator changes for onshore wind energy

Indicator	Development trends/expected indicator changes over time
CF	- Slight increase expected over time - First and third decade foresee a 5% point increase on lower range and no change on the higher range - Second decade foresees a 5% point increase on higher range, but not on lower range
REL	- No change over time expected
IC	- Considerable reduction over time according to [393] - Price of first decade drops to 88% of initial price - Price of second decade drops to 81% of initial price - Price of third decade drops to 77% of initial price
O&MC	- Considerable reduction over time according to [394], [395]
LT	- No change over time expected
$LCCO_2E$	- Minor reduction over time is expected - 1% reduction per decade on lower range of $LCCO_2E$ - 2% reduction per decade on higher range of $LCCO_2E$
LU	- Reductions are foreseen due to technology development (mainly increase of MW per turbine and Repowering) [396] - 5% reduction potential per decade on land use - reductions are based on rounded values
JC	- Minor increase in jobs due to repowering process (2% per decade)
PA	- No change over time expected

Table D-4: Development trends and expected indicator changes for geothermal energy

Indicator	Development trends/expected indicator changes over time
CF	- No change over time expected
REL	- No change over time expected, since very high levels of reliability are already being achieved
IC	- Considerable reduction for flash steam and binary cycle plants over time according to [394] - Steeper decline expected in first decade - For dry steam only minor reduction expected since costs are already at a lower level (5% per decade)
O&MC	- Considerable reduction over time for binary cycles according to [394] (~5% per decade) - Similar trend is expected for all other geothermal technology choices [315] - 5% reduction potential per decade on lower range of O&M - 10% reduction potential per decade on higher range of O&M
LT	- No change over time expected
$LCCO_2E$	- Minor reduction over time is expected - 1% reduction per decade on lower range of $LCCO_2E$ - 2% reduction per decade on higher range of $LCCO_2E$
LU	- No change over time expected
JC	- No change over time is expected on the lower range JC - Considerable reduction is expected on the higher range of JC (5% per decade)
PA	- No change over time expected

Table D-5: Development trends and expected indicator changes for hydro

Indicator	Development trends/expected indicator changes over time
CF	- No major changes in the capacity factor of hydropower are expected since the CF depends highly on the seasonal availability of water - Different site locations will receive higher or lower CF that are expected to be within the given range of each technology option
REL	- Minor changes are expected over time for run-of-the river and conventional hydroelectric; pumped-storage remains the same over time - For run-of-the-river plants a slight increase up to 95% in 30 years' time is expected - conventional hydroelectric increases to 93-98% (1% value increase per decade)
IC	- Considerable reduction over time for all hydro technology options [315]
O&MC	- 5% reduction per decade on lower range of cost estimate - 10% reduction per decade on higher range of cost estimate
LT	- No change over time expected
$LCCO_2E$	- No change over time expected
LU	- Minor/considerable reduction seems realistic; whereby lower range remains nearly unchanged - 1% reduction potential per decade on lower range of land use - 5% reduction potential per decade on higher range of land use - Reductions are based on rounded values
JC	- Minor reduction of 2% per decade might be reasonable due to automation of processes
PA	- No change over time expected - Hydro power is the most established form of RET - It receives a relatively high public acceptance which is not foreseen to change considerably over time

Table D-6: Development trends and expected indicator changes for offshore wind energy

Indicator	Development trends/expected indicator changes over time
CF	- The current differentiation between fixed and floating offshore wind foundation continues over time since slightly better conditions are expected in open waters further of the coast [316] - in the long-term CF up to 60% might be achievable [397] - for fixed foundation types an increase of the lower range is expected in the first decade; in second and third decade both, lower and upper range, increase - floating foundation types have a moderate increase on lower and upper range over first and second decade; in third decade a slightly higher increase in foreseen to reach the 60%
REL	- No change has been undertaken over the first 2 decades - For the last decade a minor increase by 1% score has been considered for all offshore wind technology choices
IC	- Expected cost reduction according to [292]
O&MC	- Expected cost reduction according to [398], (conversion rate not considered since initial values would be higher than actual values)
LT	- No change over time expected
$LCCO_2E$	- Minor reduction over time is expected - 1% reduction per decade on lower range of $LCCO_2E$ - 2% reduction per decade on higher range of $LCCO_2E$
LU	- Reductions are foreseen due to technology development (mainly increase of MW per turbine) - 5% reduction potential per decade on land use - reductions are based on rounded values
JC	- The number of jobs per MW is expected to remain nearly constant over time - More complex and bigger system seem to require more maintenance, despite having fewer of them installed
PA	- No change over time expected

Table D-7: Development trends and expected indicator changes for wave energy

Indicator	Development trends/expected indicator changes over time
CF	- Considerable increases over time horizons are expected [399], [400]
REL	- Minor increases over time horizons are expected [292], [399]
IC	- Significant reductions over time horizons are expected [399], [400]
O&MC	- Significant reductions of high range over time horizons are expected [292], [400] - Lower range also decreases slightly over time
LT	- No change over time expected
$LCCO_2E$	- Minor reduction over time is expected - 1% reduction per decade on lower range of $LCCO_2E$ - 2% reduction per decade on higher range of $LCCO_2E$
LU	- Considerable reductions are foreseen due to technology development (mainly increase of MW per turbine) - 5% reduction potential per decade on land use - Reductions are based on rounded values
JC	- No change over time - More complex and bigger system seem to require more maintenance, despite having fewer of them installed
PA	- No change over time expected

Table D-8: Development trends and expected indicator changes for tidal energy

Indicator	Development trends/expected indicator changes over time
CF	- Considerable increase similar to floating offshore wind technology choices [400]
REL	- Minor increases over time horizons are expected [401]
IC	- Significant reductions over time horizons are expected [292], [400]
O&MC	- Significant reductions of high range over time horizons are expected [292], [400] - Lower range also decreases slightly over time
LT	- No change over time expected
$LCCO_2E$	- Minor reduction over time is expected - 1% reduction per decade on lower range of $LCCO_2E$ - 2% reduction per decade on higher range of $LCCO_2E$
LU	- Considerable reductions are foreseen due to technology development (mainly increase of MW per turbine) - 5% reduction potential per decade on land use - Reductions are based on rounded values
JC	- No change over time - More complex and bigger system seem to require more maintenance, despite having fewer of them installed
PA	- No change over time expected

Table D-9: Modified data set for each attribute by RET in 10 years' time

Technology	CF (%)	REL (%)	IC (€/kW$_{el}$)	O&MC (€/kW/a)	LT (years)	LCCO$_2$E (gCO$_2$/kWh$_{el}$)	LU (m^2/MW)	JC (#)	PA (-)
Stoke boiler	90	94	3430	139	20	62	4750	4	5
Fluidized bed boiler	90	96	3430	139	20	62	4750	4	5
Combined heat and power (CHP)	90	80	3430	139	20	76	4750	4	5
Fixed bed gasifiers	90	88	4590	139	20	66	4750	4	5
Fluidized bed gasifiers	90	98	4590	139	20	66	4750	4	5
Entrained flow gasifiers	90	85	4590	139	20	66	4750	4	5
Pyrolysis	88	92	1940	139	20	66	4750	24	5
Anaerobic digestion	91	83	4845	139	20	66	4750	24	5
Thin-film technologies	15	97	2750	35	20	43	74	33	8
Emerging PV	12	97	2750	35	20	54	74	33	8
Multi-junction Cells	26	97	2750	35	20	54	74	33	8
Single-Junction GaAs	20	97	2750	35	20	52	74	33	8
Crystalline Si Cells	18	97	2750	35	20	43	74	33	8
Parabolic Trough	66	94	6700	58	30	23	79	6	8
Horizontal axis lift turbine	38	98	1760	22	20	31	750	13	6.5
Dry Steam power plants	90	96	2375	92	28	38	24	10	5.5
Flash steam power plants	90	96	2300	147	28	57	24	10	5.5
Binary cycle power plants	90	80	3300	136	30	38	24	10	5.5
Run-of-the-river	68	92	2330	47	60	4	420	18	7
Conventional hydroelectric	45	94	2330	47	60	6	420	18	7
Pumped-storage	20	99	2330	47	60	16	420	18	7
Offshore fixed	40	98	3200	100	20	21	750	20	6.5
Offshore floating	46	98	4200	100	20	21	750	20	7.5
Wave	36	90	4000	250	20	22	266	9	7.5
Tidal	38	85	5900	135	20	22	266	11	7.5
max	91	99	6700	250	60	76	4750	33	8
min	12	80	1760	22	20	4	24	4	5

Table D-10: Swing weights for MCDA in 10 years' time

Criteria	Criteria 'Swings'		m_q	w_q
IC ($/kW$_{el}$)	a decrease in IC from 6700-1760 leads to highest satisfaction		100	15.1%
LCCO$_2$E (gCO$_2$/kWh$_{el}$)	a decrease in LCCO$_2$E from 76-4 is equivalent to a IC reduction from	6700-2200	91	13.7%
LU (m2/kW)	a decrease in LU from 4750-24 is equivalent to a IC reduction from	6700-2500	85	12.8%
PA (-)	an increase in PA from 5-8 is equivalent to a IC reduction from	6700-2700	81	12.2%
O&M ($/kW/a)	a decrease in O&MC from 250-22 is equivalent to a IC reduction from	6700-3000	75	11.3%
JC (#/MW)	an increase in JC from 4-33 is equivalent to a IC reduction from	6700-3100	73	11.0%
CF (%)	an increase in CF from 12-91 is equivalent to a IC reduction from	6700-3300	69	10.4%
REL (%)	an increase in REL from 80-99 is equivalent to a IC reduction from	6700-3200	65	9.8%
LT (years)	an increase in LT from 20-60 is equivalent to a IC reduction from	6700-5500	24	3.7%
Total			663	100.0%

Table D-11: Modified data set for each attribute by RET in 20 years' time

Technology	CF (%)	REL (%)	IC (€/kW_{el})	O&MC (€/kW/a)	LT (years)	$LCCO_2E$ (gCO_2/kWh_{el})	LU (m^2/MW)	JC (#)	SA (-)
Stoke boiler	90	95	3240	133	20	61	4510	4	5
Fluidized bed boiler	90	97	3240	133	20	61	4510	4	5
Combined heat and power (CHP)	90	85	3240	133	20	75	4510	4	5
Fixed bed gasifiers	90	90	4215	133	20	65	4510	4	5
Fluidized bed gasifiers	90	98	4215	133	20	65	4510	4	5
Entrained flow gasifiers	90	87	4215	133	20	65	4510	4	5
Pyrolysis	88	93	1880	133	20	65	4510	23	5
Anaerobic digestion	91	85	4430	133	20	65	4510	23	5
Thin-film technologies	16	97	1925	29	20	43	71	32	8
Emerging PV	13	97	1925	29	20	53	71	32	8
Multi-junction Cells	29	97	1925	29	20	53	71	32	8
Single-Junction GaAs	22	97	1925	29	20	51	71	32	8
Crystalline Si Cells	20	97	1925	29	20	43	71	32	8
Parabolic Trough	57	96	5630	56	30	22	78	6	8
Horizontal axis lift turbine	43	98	1620	19	20	30	710	14	6.5
Dry Steam power plants	90	96	2255	85	28	37	24	10	5.5
Flash steam power plants	90	96	2200	134	28	57	24	10	5.5
Binary cycle power plants	90	80	3000	124	30	37	24	10	5.5
Run-of-the-river	68	94	2130	43	60	4	401	18	7
Conventional hydroelectric	45	95	2130	43	60	6	401	18	7
Pumped-storage	20	99	2130	43	60	16	401	18	7
Offshore fixed	45	98	3050	83	20	21	710	20	6.5
Offshore floating	50	98	4000	83	20	21	710	20	7.5
Wave	39	95	2850	190	20	22	253	9	7.5
Tidal	45	90	4400	90	20	22	253	11	7.5
max	91	99	5630	190	60	75	4510	32	8
min	13	80	1620	19	20	4	24	4	5

Table D-12: Swing weights for MCDA in 20 years' time

Criteria	Criteria 'Swings'		m_q	w_q
IC ($/$kW_{el}$)	a decrease in IC from 5630-1620 leads to highest satisfaction		100	15.2%
$LCCO_2E$ (gCO_2/kWh_{el})	a decrease in $LCCO_2E$ from 75-4 is equivalent to a IC reduction from	5630-2050	89	13.6%
LU (m2/kW)	a decrease in LU from 4510-24 is equivalent to a IC reduction from	5630-2300	83	12.7%
PA (-)	an increase in PA from 5-8 is equivalent to a IC reduction from	5630-2400	81	12.3%
O&M ($/kW/a)	a decrease in O&MC from 190-19 is equivalent to a IC reduction from	5630-2650	74	11.3%
JC (#/MW)	an increase in JC from 4-32 is equivalent to a IC reduction from	5630-2750	72	11.0%
CF (%)	an increase in CF from 13-91 is equivalent to a IC reduction from	5630-2900	68	10.4%
REL (%)	an increase in REL from 80-99 is equivalent to a IC reduction from	5630-3050	64	9.8%
LT (years)	an increase in LT from 20-60 is equivalent to a IC reduction from	5630-4650	24	3.7%
Total			656	100.0%

Table D-13: Modified data set for each attribute by RET in 30 years' time

Technology	CF (%)	REL (%)	IC (€/kW$_{el}$)	O&MC (€/kW/a)	LT (years)	LCCO$_2$E (gCO$_2$/kWh$_{el}$)	LU (m^2/MW)	JC (#)	SA (-)
Stoke boiler	90	96	3000	127	20	60	4280	4	5
Fluidized bed boiler	90	97	3000	127	20	60	4280	4	5
Combined heat and power (CHP)	90	88	3000	127	20	74	4280	4	5
Fixed bed gasifiers	90	91	3875	127	20	64	4280	4	5
Fluidized bed gasifiers	90	98	3875	127	20	64	4280	4	5
Entrained flow gasifiers	90	88	3875	127	20	64	4280	4	5
Pyrolysis	90	94	1825	127	20	64	4280	23	5
Anaerobic digestion	91	88	4055	127	20	64	4280	23	5
Thin-film technologies	17	98	1550	24	20	42	68	30	8
Emerging PV	14	98	1550	24	20	52	68	30	8
Multi-junction Cells	32	98	1550	24	20	52	68	30	8
Single-Junction GaAs	24	98	1550	24	20	50	68	30	8
Crystalline Si Cells	22	98	1550	24	20	42	68	30	8
Parabolic Trough	58	97	4750	53	30	22	77	6	8
Horizontal axis lift turbine	45	98	1545	17	20	30	675	14	6.5
Dry Steam power plants	90	96	2140	78	28	37	24	9	5.5
Flash steam power plants	90	96	2100	123	28	56	24	9	5.5
Binary cycle power plants	90	80	2800	114	30	37	24	9	5.5
Run-of-the-river	68	95	1950	39	60	4	383	18	7
Conventional hydroelectric	45	96	1950	39	60	6	383	18	7
Pumped-storage	20	99	1950	39	60	16	383	18	7
Offshore fixed	50	99	2900	73	20	20	675	20	6.5
Offshore floating	55	99	3800	73	20	20	675	20	7.5
Wave	41	98	2125	138	20	21	240	9	7.5
Tidal	55	95	3400	60	20	21	240	11	7.5
max	91	99	4750	138	60	74	4280	30	8
min	14	80	1545	17	20	4	24	4	5

Table D-14: Swing weights for MCDA in 30 years' time

Criteria	Criteria 'Swings'		m_q	w_q
IC ($/kW$_{el}$)	a decrease in IC from 4750-1545 leads to highest satisfaction		100	15.4%
LCCO$_2$E (gCO$_2$/kWh$_{el}$)	a decrease in LCCO$_2$E from 74-4 is equivalent to a IC reduction from	4750-1900	89	13.7%
LU (m2/kW)	a decrease in LU from 4280-24 is equivalent to a IC reduction from	4750-2100	83	12.7%
PA (-)	an increase in PA from 5-8 is equivalent to a IC reduction from	4750-2200	80	12.2%
O&M ($/kW/a)	a decrease in O&MC from 138-17 is equivalent to a IC reduction from	4750-2400	73	11.3%
JC (#/MW)	an increase in JC from 4-30 is equivalent to a IC reduction from	4750-2450	72	11.0%
CF (%)	an increase in CF from 14-91 is equivalent to a IC reduction from	4750-2600	67	10.3%
REL (%)	an increase in REL from 80-99 is equivalent to a IC reduction from	4750-2700	64	9.8%
LT (years)	an increase in LT from 20-60 is equivalent to a IC reduction from	4750-4000	23	3.6%
Total			651	100.0%

E. Appendix E – Energy data Azores

Table E-1: Final energy demand in the Azores, in 2008 [80]

Energy carriers		Residential [MWh]	Primary sector [MWh]	Secondary sector [MWh]	Tertiary sector [MWh]	Transports [MWh]	Total [MWh]
Centralized energy services	Electricity	253,540	12,818	118,067	364,101	2,031	750,557
Fossil fuels	Fuel oil	0		255,606			255,606
	Diesel	0	292,760			976,481	1,269,241
	Gasoline	0				385,277	385,277
	LPG	263,156					263,156
Total		**516,696**	**305,579**	**373,673**	**364,101**	**1,363,789**	**2,923,837**
Total in %		**17.7%**	**10.5%**	**12.8%**	**12.5%**	**46.6%**	

Table E-2: Electric vehicles predicted per island [80]

Island	Number of EVs	Percentage of families with EV
Santa Maria	670	33.23%
São Miguel	17,956	41.16%
Terceira	2,000	10.14%
Faial	2176	39.82%
Graciosa	150	8.87%
Pico	1,445	28.57%
São Jorge	400	11.63%
Flores	50	3.34%
Corvo	25	12.82%

Table E-3: Actions for secondary energy production [80]

Island	Type of generation	Actions	Responsible for the implementation	Implementation schedule Starting year	Ending year
Santa Maria	Wind	Enlargement of Figueiral Wind Farm – 0.6MW	EDA	2012	2012
	Wind	New Wind Farm or enlargement of the existing one – 0.46MW	Private companies or EDA	2016	2017
	Solar PV	Installation of 1.2MW PV in the residential sector	Citizens	2016	2020
São Miguel	Hydro	Reversible hydro power plant at Lagoa das Furnas – 11.1MW	EDA	2015	2017
	Wind	Graminhais Wind Farm – 9MW	EDA	2011	2012
	Solar PV	Installation of 2.4MW PV in the residential ssector	Citizens	2016	2020
	Geothermal	Enlargement of Pico Vermelho power plant – 7.5MW	EDA	2014	2016
	Biomass	Biomass cogeneration power plant – 4MW	Private company	2016	2017
Terceira	Wind	Enlargement of Serra do Cume Wind Farm – 4.5MW	EDA	2011	2012
	Wind	New Wind Farms – 2MW	Private companies	2013	2014
	Solar PV	Installation of 1MW PV in the residential sector	Citizens	2016	2020
	Geothermal	New geothermal power plant at Terceira island – 3MW	Geoterceira EDA	2014	2015
	Geothermal	Enlargement of the geothermal power plant – 3MW	Geoterceira EDA	2017	2018
	Biomass	Biomass cogeneration power plant – 2MW	Private company	2013	2014
Faial	Wind	Enlargement of Lomba de Frades wind farm from 1.8MW to 4.25MW	EDA	2012	2012
	Solar PV	Installation of 1.3MW PV in the residential sector	EDA	2014	2020
Graciosa	Wind	Enlargement of Serra Branca Wind Farm 0.46MW	EDA	2012	2013
	Solar PV	Installation of 0.4MW PV in the residential sector	Citizens	2016	2020
	Biomass	Biomass cogeneration plant – 1.5MW	Private company	2015	2016
Pico	Wind	Enlargement of Terras do Canto wind farm – 0.6MW	EDA	2011	2012
	Wind	New wind farm or enlargement of the existing one – 3.6MW	EDA or private companies	2015	2016
	Solar PV	Installation of 1.2MW PV in the residential sector	Citizens	2016	2020
São Jorge	Wind	Enlargement of Pico da Urze wind farm 0.44MW	EDA	2011	2012
	Wind	New wind farm or enlargement of the existing one – 1MW	EDA or private companies	2016	2017
	Solar PV	Installation of 0.4MW PV in the residential sector	Citizens	2016	2020
	Biomass	Biomass cogeneration power plant – 1.5MW	Private company	2014	2015
Flores	Hydro	Enlargement of Além Fazenda – 0.128MW	EDA	2012	2013
	Hydro	New hydro of Ribeira Grande – 1.1MW	EDA	2015	2016
Corvo	Wind	New Wind Farm – 0.3MW	EDA	2014	2016

F. Appendix F – Energy consumption and breakdown of São Miguel Island

Table F-1: Breakdown of São Miguel´s 2009 electricity consumption by service in kWh [331]

Consumo de energia eléctrica	Tensão		Auto-consumo	
Sector	Alta	Baixa		Total
01 - Agricultura, produção animal	1,233,532	3,423,011	1,401,672	6,058,215
02 - Silvicultura		14,208		14,208
03 - Pesca	638,615	871,527		1,510,142
08 - Outras indútrias extractivas	1,501,563	38,342		1,539,905
10 - Indústrias alimentares	48,357,417	4,031,644	662,772	53,051,833
11 - Indústria das bebidas	1,069,681	200,564		1,270,245
12 - Indústria do tabaco	1,015,701	38,170		1,053,871
13 - Fabricação de têxteis		32,075		32,075
14 - Indústria do vestuário		186,879		186,879
15 - Indústria do couro		280		280
16 - Indústrias da madeira e cortiça	624,164	250,161		874,325
18 - Impressão e reprodução de suportes gravados	343,938	811,477		1,155,415
20 - Fabricação de produtos quimicos		117,934		117,934
22 - Fabricação de artigos de borracha e de matérias plásticas	263,041	955		263,996
23 - Fabricação de outros produtos minerais não metálicos	9,815,272	324,187		10,139,459
24 - Indústrias metalúrgicas de base		9,064		9,064
25 - Fabricação de produtos metálicos	999,773	529,649		1,529,422
28 - Fabricação de máquinas e de equipamentos, n.e.		7,914		7,914
29 - Fabricação de veículos automóveis		1,351		1,351
30 - Fabricação de outro equipamento de transporte		18,285		18,285
31 - Fabrico de mobiliário e de colchões		89,328		89,328
32 - Outras indústrias transformadoras		15,324		15,324
33 - Reparação, manutenção e instalação de máquinas		48,758		48,758
35 - Electricidade, gás, vapor, água quente e fria e ar frio	999,999	96,903		1,096,902
36 - Captação, tratamento e distribuição de água	1,390,349	343,927		1,734,276
38 - Recolha, tratamento e eliminação de resíduos		11,551		11,551
41 - Promoção imobiliária ; construção	981,061	3,174,784		4,155,845
42 - Engenharia civil	1,706,778	880,559		2,587,337
43 - Actividades especializadas de construção	88,167	702,006		790,173
45 - Comércio, manutenção e reparação de automóveis e motociclos	680,999	2,240,969		2,921,968
46 - Comércio por grosso, excepto automóveis e motociclos	4,553,631	6,333,040		10,886,671
47 - Comércio a retalho, excepto automóveis e motociclos	19,481,194	20,578,513		40,059,707
49 - Transportes terrestres e por oleodutos ou gasodutos	763,214	269,041		1,032,255
50 - Transportes por água		42,282		42,282
51 - Transportes aéreos	270,003	29,740		299,743
52 - Armazenagem e actividades auxiliares dos transportes	12,467,313	1,202,118		13,669,431
53 - Actividades postais e de courier	1,035,328	150,488		1,185,816
55 - Alojamento	14,467,260	2,656,245		17,123,505
56 - Restauração e similares	90,240	16,729,992		16,820,232
58 - Actividades de edição		147,880		147,880
59 - Actividades cinematográficas, de vídeo		339,958		339,958
60 - Actividades de rádio e de televisão	860,833	426,868		1,287,701
61 - Telecomunicações	3,094,104	4,230,313		7,324,417
62 - Consultoria e programação informática		8,869		8,869
63 - Actividades dos serviços de informação		4,348		4,348

Table F-1 continued				
64 - Actividades de serviços financeiros	1,776,234	2,749,361		4,525,595
65 - Seguros, fundos de pensões, excepto segurança social obrigatória		545,147		545,147
66 - Actividades auxiliares de serviços financeiros e seguros		40,905		40,905
68 - Actividades imobiliárias	4,124,103	2,741,851		6,865,954
69 - Actividades jurídicas e de contabilidade	419,365	435,993		855,358
70 - Actividades das sedes sociais e consultoria para gestão		46,054		46,054
71 - Actividades de arquitectura, engenharia e técnicas afins	315,740	275,968		591,708
72 - Actividades de investigação científica e de desenvolvimento	312,815	54,099		366,914
73 - Publicidade, estudos de mercado e sondagens de opinião		209,331		209,331
74 - Outras actividades de consultoria, científicas e técnicas		168,994		168,994
75 - Actividades veterinárias		66,212		66,212
77 - Actividades de aluguer		376,231		376,231
79 - Agências de viagem, operadores turísticos		270,370		270,370
80 - Investigação e segurança	72,468	16,552		89,020
81 - Manutenção de edifícios e jardins		97,271		97,271
82 - Serviços administrativos e de apoio às empresas	10,121	463,654		473,775
84 - Administração pública e defesa; segurança social obrigatória	8,591,131	10,051,872		18,643,003
85 - Educação	4,664,860	1,827,854		6,492,714
86 - Actividades de saúde humana	8,956,067	1,151,547		10,107,614
87 - Apoio social com alojamento	934,062	707,329		1,641,391
88 - Apoio social sem alojamento	45,573	1,217,256		1,262,829
90 - Teatro, música e dança	185,926	149,645		335,571
91 - Bibliotecas, arquivos e museus	536,711	3,028		539,739
92 - Lotarias e outros jogos de apostas		15,803		15,803
93 - Actividades desportivas, de diversão e recreativas	634,772	1,538,950		2,173,722
94 - Organizações associativas	71,666	1,667,400		1,739,066
95 - Reparação de computadores e de bens de uso pessoal		128,381		128,381
96 - Outras actividades de serviços pessoais	204,773	860,046		1,064,819
98 - Consumo doméstico		133,376,752		133,376,752
99 - Actividades dos org. internacionais		101,635		101,635
993 - Iluminação vias públicas e sinalização semafórica		16,974,446		16,974,446
Total	**160,649,557**	**249,991,418**	**2,064,444**	**412,705,419**

Table F-2: Breakdown of São Miguel´s 2009 electricity consumption by sector [331]

Sector	Percentage
Residential	32.61%
Commercial	45.41%
Industry	21.65%
Transport	0.33%

Table F-3: Cover for load profile and time series of Janus and Aurora 10 for São Miguel

Input data for the creation of scenarios			Output Janus RL/LS10
General data and assumptions			
Start year	-	2013	2023
Total primary energy	TJ/y	9,404	7,946
	GWh/y	2,612	2,207

1

Power unit type	Number of units	Installed capacity (MW)	Approx. full load hours (h/y) *	Capacity factor	Max full load hours (h/y) **	Annual generation (GWh/y) *	Built in	
Fuel - Caldeirão	8	98.06	1,933	22%	3,500	189.57	1987	in range
Geoth. - Pico Vermelho	1	13.00	7,675	88%	>8.000	99.78	2006	in range
Geoth. - Rib. Grande	1	16.60	4,487	51%	>8.000	74.49	1994	in range
Hydro - Tambores	1	0.09	1,606	18%	>4.000	0.15	1909	phase-out
Hydro - Fábrica Nova	1	0.61	285	3%	>4.000	0.17	1927	phase-out
Hydro - Canário	1	0.40	6,303	72%	>4.000	2.52	1991	in range
Hydro - Foz da Ribeira	1	0.80	5,918	68%	>4.000	4.73	1990	in range
Hydro - Ribeira da Praia	1	0.80	4,660	53%	>4.000	3.73	1991	in range
Hydro - Salto do Cabrito	1	0.67	6,804	78%	>4.000	4.56	2006	in range
Hydro - Túneis	1	1.66	6,381	73%	>4.000	10.58	1951	in range
Other (Biogas and PV)	1	0.12	3,700	42%	N/A	0.44	2010	in range
Wind - Graminhais	10	9.00	2,384	27%	2,500	21.46	2012	in range
Total		141.81				412.18		

2

Electricity consumption		GWh/y	412.18	474.01
Share of electricity on total primary energy demand		%	15.78	20.16%
Total installed capacity		MW	141.81	
Available installed RES capacity for electricity generation		MW	43.66	
Available installed fossil fuel capacity for electricity generation		MW	98.06	
Annual energy demand	increase	%/y	-	
	decrease	%/y	1.0	
Annual electricity demand	increase	%/y	1.5	
	decrease	%/y	-	

4

	current		in 10 years		Saving potential by sector
Breakdown final energy consumption by sector	GWh/y *	% *	GWh/y *	% *	
Residential		32.6%		34.0%	26%
Commercial		45.4%		46.4%	21%
Industry		21.7%		18.3%	0%
Transportation		0.3%		1.3%	9%
Projected electricity consumption after applying saving potential			GWh/y		385.36

5

Total electricity generation to be covered from RES	GWh/y	284.44
Electricity generation required from new RES in 10 years	GWh/y	62.15
Fossil fuel based in 10 years	GWh/y	100.92
Maximum electricity available from fossil fuel units	GWh/y	343.22
Peak power demand over the year	MW	65.40
Available peak power: fossil fuel capacity + baseload RES * capacity factor	MW	119.97

* Requires the information of either approx. full load hours or annual generation or percentage or annual demand

** shall determine the upper bound of full load hours under which the fossil fuel units can be operated

Table F-4: Cover for load profile and time series of Janus and Aurora 20 for São Miguel

Input data for the creation of scenarios			Output Janus RL/LS20
General data and assumptions			
Start year	-	2013	2033
Total primary energy	TJ	9,404	6,346
	GWh	2,612	1,763

1

Power unit type	Number of units	Installed capacity (MW)	Approx. full load hours (h/y) *	Capacity factor	Max full load hours (h/y) **	Annual generation (GWh/y) *	Built in	
Fuel - Caldeirão	8	98.06	1,933	22%	3,500	189.57	1987	phase-out
Geoth. - Pico Vermelho	1	13.00	7,675	88%	>8.000	99.78	2006	in range
Geoth. - Rib. Grande	1	16.60	4,487	51%	>8.000	74.49	1994	phase-out
Hydro - Tambores	1	0.09	1,606	18%	>4.000	0.15	1909	phase-out
Hydro - Fábrica Nova	1	0.61	285	3%	>4.000	0.17	1927	phase-out
Hydro - Canário	1	0.40	6,303	72%	>4.000	2.52	1991	in range
Hydro - Foz da Ribeira	1	0.80	5,918	68%	>4.000	4.73	1990	in range
Hydro - Ribeira da Praia	1	0.80	4,660	53%	>4.000	3.73	1991	in range
Hydro - Salto do Cabrito	1	0.67	6,804	78%	>4.000	4.56	2006	in range
Hydro - Túneis	1	1.66	6,381	73%	>4.000	10.58	1951	phase-out
Other (Biogas and PV)	1	0.12	3,700	42%	N/A	0.44	2010	in range
Wind - Graminhais	10	9.00	2,384	27%	2,500	21.46	2012	phase-out
Total		141.81				412.18		

2

Electricity consumption		GWh	412.18	535.84
Share of electricity on total primary energy demand		%	15.78	30.40
Total installed capacity		MW	141.81	
Available installed RES capacity for electricity generation		MW	43.05	
Available installed fossil fuel capacity for electricity generation		MW	65.38	
Annual energy demand	increase	%/y	-	
	decrease	%/y	0.5	
Annual electricity demand	increase	%/y	1.5	
	decrease	%/y	-	

4

	current		in 20 years		Saving potential by sector
Breakdown final energy consumption by sector	GWh/y *	% *	GWh/y *	% *	
Residential		32.6%		35.4%	37%
Commercial		45.4%		44.4%	24%
Industry		21.7%		17.8%	0%
Transportation		0.3%		2.4%	15%
Projected electricity consumption after applying saving potential			GWh/y		406.62

5

Total electricity generation to be covered from RES	GWh/y	346.27
Electricity generation required from new RES in 20 years	GWh/y	230.50
Fossil fuel based in 20 years	GWh/y	60.36
Maximum electricity available from fossil fuel units	GWh/y	228.82
Peak power demand over the year	MW	69.01
Available peak power: fossil fuel capacity + baseload RES * capacity factor	MW	87.29

* Requires the information of either approx. full load hours or annual generation or percentage or annual demand

** shall determine the upper bound of full load hours under which the fossil fuel units can be operated

Table F-5: Cover for load profile and time series of Janus and Aurora 30 for São Miguel

Input data for the creation of scenarios			Output Janus RL/LS30
General data and assumptions			
Start year	-	2013	2043
Total primary energy	TJ	9,404	5,414
	GWh	2,612	1,504

1

Power unit type	Number of units	Installed capacity (MW)	Approx. full load hours (h/y) *	Capacity factor	Max full load hours (h/y) **	Annual generation (GWh/y) *	Built in	
Fuel - Caldeirão	8	98.06	1,933	22%	3,500	189.57	1987	phase-out
Geoth. - Pico Vermelho	1	13.00	7,675	88%	>8.000	99.78	2006	phase-out
Geoth. - Rib. Grande	1	16.60	4,487	51%	>8.000	74.49	1994	phase-out
Hydro - Tambores	1	0.09	1,606	18%	>4.000	0.15	1909	phase-out
Hydro - Fábrica Nova	1	0.61	285	3%	>4.000	0.17	1927	phase-out
Hydro - Canário	1	0.40	6,303	72%	>4.000	2.52	1991	in range
Hydro - Foz da Ribeira	1	0.80	5,918	68%	>4.000	4.73	1990	in range
Hydro - Ribeira da Praia	1	0.80	4,660	53%	>4.000	3.73	1991	in range
Hydro - Salto do Cabrito	1	0.67	6,804	78%	>4.000	4.56	2006	in range
Hydro - Túneis	1	1.66	6,381	73%	>4.000	10.58	1951	phase-out
Other (Biogas and PV)	1	0.12	3,700	42%	N/A	0.44	2010	phase-out
Wind - Graminhais	10	9.00	2,384	27%	2,500	21.46	2012	phase-out
Total		141.81				412.18		

2

Electricity consumption		GWh	412.18	535.84
Share of electricity on total primary energy demand		%	15.78	35.63
Total installed capacity		MW	141.81	
Available installed RES capacity for electricity generation		MW	26.45	
Available installed fossil fuel capacity for electricity generation		MW	32.69	
Annual energy demand	increase	%/y	-	
	decrease	%/y	0.5	
Annual electricity demand	increase	%/y	1.0	
	decrease	%/y	-	

4

	current		in 30 years		Saving potential by sector
Breakdown final energy consumption by sector	GWh/y *	% *	GWh/y *	% *	
Residential		32.6%		35.0%	54%
Commercial		45.4%		45.0%	33%
Industry		21.7%		17.0%	0%
Transportation		0.3%		3.0%	22%
Projected electricity consumption after applying saving potential			GWh/y		351.46

5

Total electricity generation to be covered from RES	GWh/y	346.27
Electricity generation required from new RES in 30 years	GWh/y	330.73
Fossil fuel based in 30 years	GWh/y	5.19
Maximum electricity available from fossil fuel units	GWh/y	114.41
Peak power demand over the year	MW	59.65
Available peak power: fossil fuel capacity + baseload RES * capacity factor	MW	46.63

* Requires the information of either approx. full load hours or annual generation or percentage or annual demand
** shall determine the upper bound of full load hours under which the fossil fuel units can be operated

Table F-6: Cover for load profile and time series of Antevorta 10 for São Miguel

Input data for the creation of scenarios			Output Antevorta RL/LS10
General data and assumptions			
Start year	-	2013	2023
Total primary energy	TJ/y	9,404	6,358
	GWh/y	2,612	1,766

1

Power unit type	Number of units	Installed capacity (MW)	Approx. full load hours (h/y) *	Capacity factor	Max full load hours (h/y) **	Annual generation (GWh/y) *	Built in	
Fuel - Caldeirão	8	98.06	1,933	22%	3,500	189.57	1987	in range
Geoth. - Pico Vermelho	1	13.00	7,675	88%	>8.000	99.78	2006	in range
Geoth. - Rib. Grande	1	16.60	4,487	51%	>8.000	74.49	1994	in range
Hydro - Tambores	1	0.09	1,606	18%	>4.000	0.15	1909	phase-out
Hydro - Fábrica Nova	1	0.61	285	3%	>4.000	0.17	1927	in range
Hydro - Canário	1	0.40	6,303	72%	>4.000	2.52	1991	in range
Hydro - Foz da Ribeira	1	0.80	5,918	68%	>4.000	4.73	1990	in range
Hydro - Ribeira da Praia	1	0.80	4,660	53%	>4.000	3.73	1991	in range
Hydro - Salto do Cabrito	1	0.67	6,804	78%	>4.000	4.56	2006	in range
Hydro - Túneis	1	1.66	6,381	73%	>4.000	10.58	1951	in range
Other (Biogas and PV)	1	0.12	3,700	42%	N/A	0.44	2010	in range
Wind - Graminhais	10	9.00	2,384	27%	2,500	21.46	2012	in range
Total		141.81				412.18		

2

Power consumption		GWh/y	412.18	474.01
Share of power on total primary energy demand		%	15.78	26.84
Total installed capacity		MW	141.81	
Available installed RET capacity for power generation		MW	43.66	
Available installed fossil fuel capacity for power generation		MW	98.06	
Annual energy demand	increase	%/y	-	
	decrease	%/y	1.0	
Annual power demand	increase	%/y	1.5	
	decrease	%/y	-	

3

Vector shifting	Final energy consumption by sector	Vector shifting by sector	Additional load through vector shifts
Residential	18%	26%	81.28
Commercial	13%	27%	59.61
Industry	23%	0%	0.00
Transportation	47%	5%	41.07
Additional power required after vector shift		GWh/y	181.96
Total power after vector shift		GWh/y	655.97

4

	current		in 10 years		Saving potential by sector
Breakdown final power consumption by sector	GWh/y *	% *	GWh/y *	% *	
Residential		32.6%		36.0%	26%
Commercial		45.4%		41.9%	21%
Industry		21.7%		15.6%	0%
Transportation		0.3%		6.5%	9%
Power required after applying saving potential			GWh/y		533.09
Share of power on total primary energy demand after vector shift and applied saving potential			%		30%

5

Total power generation to be covered from RET	GWh/y	533.09
Power generation required from new RET in 10 years	GWh/y	310.63
Fossil fuel based in 10 years	GWh/y	0.00
Maximum power available from fossil fuel units	GWh/y	343.22
Peak power demand over the year	MW	90.47
Available peak power: fossil fuel capacity + baseload RET * capacity factor	MW	119.97

* Requires the information of either approx. full load hours or annual generation or percentage or annual demand

** shall determine the upper bound of full load hours under which the fossil fuel units can be operated

Table F-7: Cover for load profile and time series of Antevorta 20 for São Miguel

Input data for the creation of scenarios			Output Antevorta RL/LS20
General data and assumptions			
Start year	-	2013	2033
Total primary energy	TJ/y	9,404	5841
	GWh/y	2,612	1622

1

Power unit type	Number of units	Installed capacity (MW)	Approx. full load hours (h/y) *	Capacity factor	Max full load hours (h/y) **	Annual generation (GWh/y) *	Built in	
Fuel - Caldeirão	8	98.06	1,933	22%	3,500	189.57	1987	phase-out
Geoth. - Pico Vermelho	1	13.00	7,675	88%	>8.000	99.78	2006	in range
Geoth. - Rib. Grande	1	16.60	4,487	51%	>8.000	74.49	1994	in range
Hydro - Tambores	1	0.09	1,606	18%	>4.000	0.15	1909	phase-out
Hydro - Fábrica Nova	1	0.61	285	3%	>4.000	0.17	1927	phase-out
Hydro - Canário	1	0.40	6,303	72%	>4.000	2.52	1991	in range
Hydro - Foz da Ribeira	1	0.80	5,918	68%	>4.000	4.73	1990	in range
Hydro - Ribeira da Praia	1	0.80	4,660	53%	>4.000	3.73	1991	in range
Hydro - Salto do Cabrito	1	0.67	6,804	78%	>4.000	4.56	2006	in range
Hydro - Túneis	1	1.66	6,381	73%	>4.000	10.58	1951	in range
Other (Biogas and PV)	1	0.12	3,700	42%	N/A	0.44	2010	in range
Wind - Graminhais	10	9.00	2,384	27%	2,500	21.46	2012	in range
Total		141.81				412.18		

2

Power consumption		GWh/y	412.18	535.84
Share of power on total primary energy demand		%	15.78	33.03
Total installed capacity		MW	141.81	
Available installed RET capacity for power generation		MW	43.05	
Available installed fossil fuel capacity for power generation		MW	65.38	
Annual energy demand	increase	%/y	-	
	decrease	%/y	0.5	
Annual power demand	increase	%/y	1.5	
	decrease	%/y	-	

3

Vector shifting	Final energy consumption by sector	Vector shifting by sector	Additional load through vector shifts
Residential	18%	50%	143.59
Commercial	13%	52%	105.46
Industry	23%	0%	0.00
Transportation	47%	10%	75.44
Power required after applying shifting potential		GWh/y	324.49
Total power after vector shift		GWh/y	860.33

4

	current		in 20 years		Saving potential by sector
Breakdown final power consumption by sector	GWh/y *	% *	GWh/y *	% *	
Residential		32.6%		37.0%	37%
Commercial		45.4%		40.5%	24%
Industry		21.7%		13.5%	0%
Transportation		0.3%		9.0%	15%
Power required after applying saving potential			GWh/y		647.26
Share of power on total primary energy demand after vector shift and applied saving potential				%	40%

5

Total power generation to be covered from RET	GWh/y	647.26
Power generation required from new RET in 20 years	GWh/y	424.97
Fossil fuel based in 20 years	GWh/y	0.00
Maximum power available from fossil fuel units	GWh/y	228.82
Peak power demand over the year	MW	109.85
Available peak power: fossil fuel capacity + baseload RET * capacity factor	MW	87.29

* Requires the information of either approx. full load hours or annual generation or percentage or annual demand
** shall determine the upper bound of full load hours under which the fossil fuel units can be operated

Table F-8: Cover for load profile and time series of Antevorta 30 for São Miguel

Input data for the creation of scenarios			**Output Antevorta RL/LS30**
General data and assumptions			
Start year	-	2013	2043
Total primary energy	TJ/y	9,404	4853.04
	GWh/y	2,612	1348.07

1

Power unit type	Number of units	Installed capacity (MW)	Approx. full load hours (h/y) *	Capacity factor	Max full load hours (h/y) **	Annual generation (GWh/y) *	Built in	
Fuel - Caldeirão	8	98.06	1,933	22%	3,500	189.57	1987	phase-out
Geoth. - Pico Vermelho	1	13.00	7,675	88%	>8.000	99.78	2006	in range
Geoth. - Rib. Grande	1	16.60	4,487	51%	>8.000	74.49	1994	phase-out
Hydro - Tambores	1	0.09	1,606	18%	>4.000	0.15	1909	phase-out
Hydro - Fábrica Nova	1	0.61	285	3%	>4.000	0.17	1927	phase-out
Hydro - Canário	1	0.40	6,303	72%	>4.000	2.52	1991	in range
Hydro - Foz da Ribeira	1	0.80	5,918	68%	>4.000	4.73	1990	in range
Hydro - Ribeira da Praia	1	0.80	4,660	53%	>4.000	3.73	1991	in range
Hydro - Salto do Cabrito	1	0.67	6,804	78%	>4.000	4.56	2006	in range
Hydro - Túneis	1	1.66	6,381	73%	>4.000	10.58	1951	in range
Other (Biogas and PV)	1	0.12	3,700	42%	N/A	0.44	2010	in range
Wind - Graminhais	10	9.00	2,384	27%	2,500	21.46	2012	phase-out
Total		141.81				412.182		

2

Power consumption		GWh/y	412.18	597.66
Share of power on total primary energy demand		%	15.78	44.33
Total installed capacity		MW	141.81	
Available installed RET capacity for power generation		MW	17.45	
Available installed fossil fuel capacity for power generation		MW	32.69	
Annual energy demand	increase	%/y	-	
	decrease	%/y	0.5	
Annual power demand	increase	%/y	1.5	
	decrease	%/y	-	

3

Vector shifting	Final energy consumption by sector	Vector shifting by sector	Additional load through vector shifts
Residential	18%	80%	190.89
Commercial	13%	82%	138.18
Industry	23%	0%	0.00
Transportation	47%	19%	119.10
Power required after applying shifting potential		GWh/y	448.16
Total power after vector shift		GWh/y	1045.83

4

	current		in 20 years		
Breakdown final power consumption by sector	GWh/y *	% *	GWh/y *	% *	Saving potential by sector
Residential		32.6%		36.9%	54%
Commercial		45.4%		39.2%	33%
Industry		21.7%		12.4%	0%
Transportation		0.3%		11.6%	22%
Power required after applying saving potential			GWh/y		675.71
Share of power on total primary energy demand after vector shift and applied saving potential				%	50%

5

Total power generation to be covered from RET	GWh/y	675.71
Power generation required from new RET in 10 years	GWh/y	549.36
Fossil fuel based in 10 years	GWh/y	0.00
Maximum power available from fossil fuel units	GWh/y	0.00
Peak power demand over the year	MW	114.67
Available peak power: fossil fuel capacity + baseload RET * capacity factor	MW	78.78

* Requires the information of either approx. full load hours or annual generation or percentage or annual demand
** shall determine the upper bound of full load hours under which the fossil fuel units can be operated

G. Appendix G – Load profiles for São Miguel scenarios

Henceforth, the load profiles for all scenarios are presented. Janus and Aurora look identical. The same color key has been applied to all figures to show the alterations in demand and due to vector shifts.

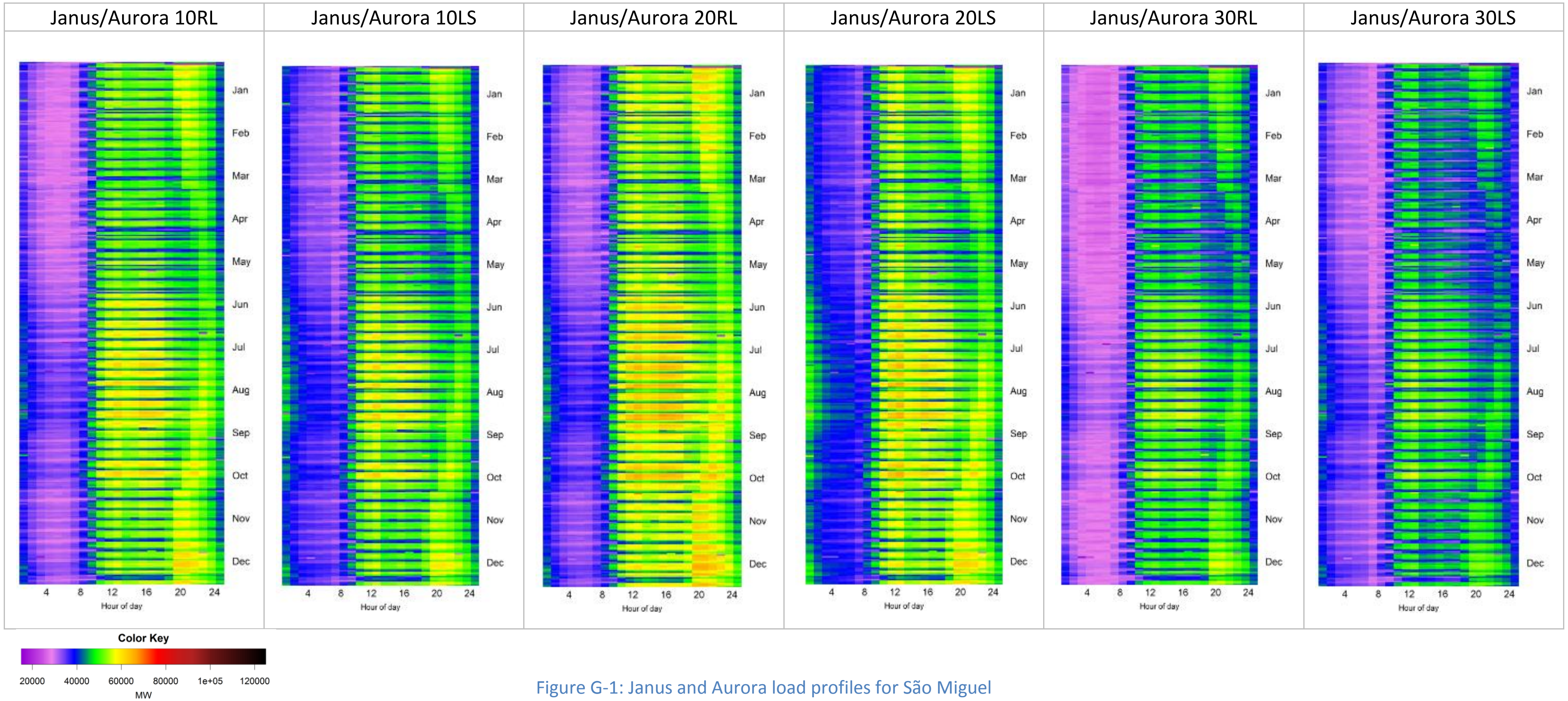
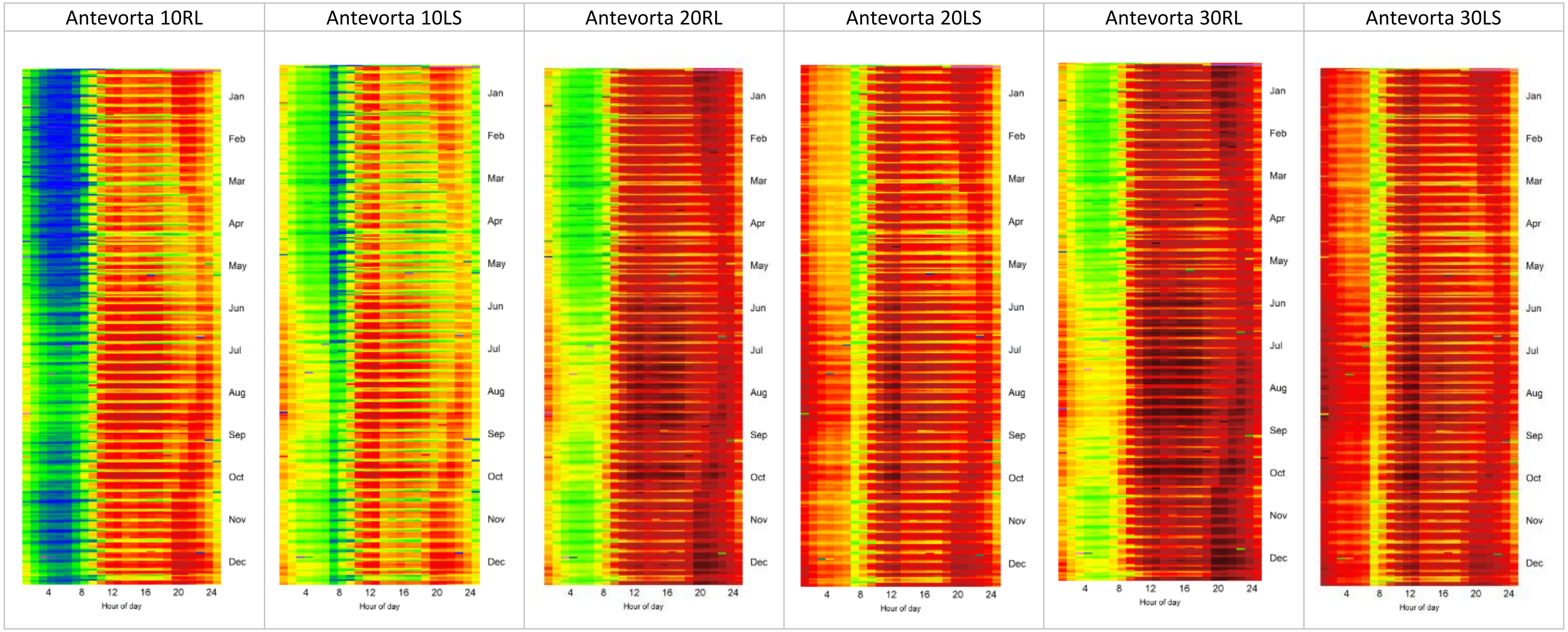


Figure G-1: Janus and Aurora load profiles for São Miguel



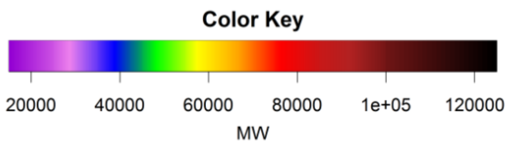


Figure G-2: Antevorta load profiles for São Miguel